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THE ROLE OF MENTAL MODELS IN DYNAMIC DECISION-MAKING

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Abstract

The complex and dynamic nature of various types of operations pose specific cognitive challenges on the decision-making process that the current training regiment of military commanders does not directly address. Therefore, DRDC Toronto is interested in researching training techniques to prepare Canadian Forces (CF) commanders and staff for decision-making in such complex and dynamic environments (12sk). This report provides a review of relevant DDM literature and mental models literature as it relates to DDM.

DDM consists of (1) decision maker(s) (2) in a complex environment (3) attempting to accomplish one or more tasks. DDM is required in environments with high risk and complexity, and involves the performance of tasks requiring multiple steps, that are inherently time sensitive, interdependent, and which exert influence over the surrounding environment as well as being influenced by it. Dynamic decision-making has been explored from different perspectives, including systems theory, psychology, and control theory from the engineering domain. These perspectives put varying amounts of focus on different aspects of DDM. What is common to all of these approaches are the assumptions that whether forming models of complex systems or making intuitive decisions based on very little information, people tend to form some sort of mental model to undertake DDM.

At a broad level, mental models can be described as personal mental representations of our world. Although there is no one agreed definition of mental models, they are generally recognized to serve three key functions: to describe, to predict, and to explain our world. The aim of this report was to explore how mental models are understood across the propositional logic, physical systems, situation model, and system dynamics perspectives. Few similarities in the descriptions of mental models were found between the domains reviewed in this report. In addition, mental models were found to be subject to a range of shortcomings that impact the accuracy of mental models (e.g., limited cognitive capacity, erroneous causal links, based on incomplete information, systemic errors).

The extent to which DDM could be supported by each of the unique approaches to understanding mental models was assessed, as well as an exploration of how well the use of mental models would be likely to support the dynamic decision-making process. This review closes with an outline of the mental models research that needs to be better explored to serve DDM, as well as an outline of the general mental models research questions that should be addressed in future research.

Résumé

Le caractère complexe et dynamique de certains types d'opérations pose des problèmes cognitifs particuliers au processus de prise de décisions que l'instruction actuelle des commandants militaires ne traite pas directement. RDDC Toronto est donc à la recherche de techniques d'instruction qui permettront de former les commandants et les membres d'état-major des Forces canadiennes (FC) à la prise de décisions dans des environnements complexes et dynamiques (12sk). Le présent compte rendu renferme un aperçu de la documentation sur la PDD et sur les modèles mentaux associés à la PDD.

La PDD implique la participation (1) d'un décideur, (2) dans un environnement complexe, (3) qui tente d'exécuter une ou plusieurs tâches. La PDD est nécessaire dans des environnements complexes où le risque est élevé. Elle implique l'exécution de tâches requérant des étapes multiples, pour lesquelles le temps est important, qui sont interdépendantes et qui exercent une influence sur le milieu environnant, tout en étant influencées par lui. La prise de décisions dynamique a été explorée à partir de différents points de vue, notamment la théorie des systèmes, la psychologie et la t héorie de contrôle dans le domaine de l'ingénierie. Ces points de vue mettent l'accent, à divers degrés, sur différents aspects de la PDD. Une hypothèse est commune à toutes ces approches : qu'il s'agisse de former des modèles de systèmes complexes ou de prendre des décisions intuitives à partir de très peu de renseignements, les gens ont tendance à développer une certaine forme de modèle mental pour effectuer une PDD.

De façon générale, on peut décrire les modèles mentaux comme des représentations mentales de notre monde. Bien qu'il n'y ait aucun consensus sur la définition des modèles mentaux, ces derniers sont généralement reconnus pour être associés à trois fonctions clés : décrire, prédire et expliquer le monde qui nous entoure. Le présent compte rendu a pour but d'explorer comment les modèles mentaux sont compris du point de vue de la logique des propositions, des systèmes causals, du modèle de situation et de la dynamique des systèmes. On a trouvé peu de similitudes dans les descriptions des modèles mentaux entre les domaines examinés dans la présente analyse. En outre, on a découvert que des modèles mentaux étaient sujets à une variété de lacunes influençant leur exactitude (p. ex., capacité cognitive limitée, liens causals erronés fondés sur des renseignements incomplets, erreurs systémiques).

On a évalué jusqu'à quel point la PDD pouvait être appuyée par chacune des approches uniques à la compréhension des modèles mentaux, de même qu'on a exploré jusqu'à quel point l'utilisation de modèles mentaux appuie le processus de prise de décisions dynamique. L'examen se termine sur les aspects de la recherche sur les modèles mentaux devant être mieux explorés pour servir la PDD, de même que sur un aperçu des questions générales relatives à la recherche sur les modèles mentaux qui devraient être traitées.

Executive Summary

The complex and dynamic nature of operations-other-than-war (OOW) (e.g., peace support, the 3-block war concept) in which Canada and allied nations are increasingly involved requires Canadian Forces (CF) officers to call upon high-level dynamic decision-making (DDM) skills to an unprecedented degree, especially at the strategic and operational levels (Rehak, Lamoureux, & Bos, 2006). The complex and dynamic nature of these various types of operations pose specific cognitive challenges on the decision-making process that the current training regiment of military commanders does not directly address. Therefore, DRDC Toronto is interested in researching training techniques to prepare Canadian Forces (CF) commanders and staff for decision-making in such complex and dynamic environments (12sk). This report provides a review of relevant DDM literature and mental models literature as it relates to DDM.

DDM consists of (1) decision maker(s) (2) in a complex environment (3) attempting to accomplish one or more tasks. DDM is required in environments with high risk and complexity, and involves the performance of tasks requiring multiple steps, that are inherently time sensitive, interdependent, and which exert influence over the surrounding environment as well as being influenced by it. Dynamic decision-making has been explored from different perspectives, including systems theory, psychology, and control theory from the engineering domain. These perspectives put varying amounts of focus on different aspects of DDM. From the systems theory perspective, for example, the focus is on creating analogies that attempt to simulate the processes that people use to manage complex systems. These analogies, moreover, represent one way to help people to form more accurate models of the system. From the psychological perspective, on the other hand, the focus is on the sets of choices that people make as they attempt to make complex decisions. Control theory's primary emphasis is on the role of feedback while managing a complex system. What is common to all of these approaches are the assumptions that whether forming models of complex systems or making intuitive decisions based on very little information, people tend to form some sort of mental model to undertake DDM.

At a broad level, mental models can be described as personal mental representations of our world. Although there is no one agreed definition of mental models, they are generally recognized to serve three key functions: to describe, to predict, and to explain our world. The aim of this report was to explore how mental models are understood across a range of relevant perspectives. The propositional logic perspective argues that reasoning depends on imagining the possibilities compatible with the premises, and drawing conclusions from these mental representations. However, there are a number of factors limiting the application of propositional models to dynamic decision-making (e.g., focus on a very small subset of reasoning tasks that involve static finite constructs, no interaction between effects of decision makers on the task or on the environment). The physical systems perspective defines mental models as the models people use in reasoning about the physical world. However, the literature on physical systems raises a number of issues pertaining to the ability of mental models to support DDM (e.g., it is unknown how such mental models are created or work in DDM environments). The situation model perspective defines a situation model a dynamic representation of a person's knowledge and understanding of the *present state* of a system, whereas the system dynamics perspective describes mental models as internal conceptual representation of an external system. In this review, few similarities in the descriptions of mental models were found between the domains reviewed in this report. This finding highlights the challenges to understanding mental models already described in mental models literature (i.e.,

lack of a clear definition, difficulty measuring mental models). In addition, mental models were also found to be subject to a range of shortcomings that impact the accuracy of mental models (e.g., limited cognitive capacity, erroneous causal links, based on incomplete information, systemic errors).

The extent to which DDM could be supported by each of the unique approaches to understanding mental models was assessed. With respect to propositional models, it was difficult to see any substantive symmetries between this perspective of mental models and DDM. Similarly, little of the literature discussion mental models of physical systems related well to DDM. As well, inconsistencies among the definition of mental models in system dynamics makes it difficult to clearly understand the role of mental models in dynamic decision making The situation model perspective was assessed to be conductive to supporting DDM as such models allow the decision maker to incorporate changes to the system into their situation model to provide them with an accurate and up-to-date vision of system status and function. However, research suggests that people are not particularly effective at creating accurate situation models.

This report also explored how well the use of mental models would be likely to support the dynamic decision-making process. With respect to the dynamic decision maker, the mental models literature contains vague descriptions of the exact mental models processes used by decision makers. In addition, the literature suggests a number of inherent limitations of decision-makers in being able to form and apply mental models, such as cognitive limitations, mental effort, heuristics, and biases. Similarly, the nature of DDM environments (i.e., complexity, feedback) and DDM tasks (i.e., time, uncertainty) are unlikely to support the use of mental models to make decisions. However, this does not mean that mental models cannot be helpful, simply that the limitations of whatever models can be formed should be recognized.

This review closes with two tables that summarize gaps in the literature. The first table outline the mental models research that needs to be better explored to serve DDM, and the second table outline general mental models research questions that should be addressed.

Sommaire

Le caractère complexe et dynamique des opérations autres que la guerre (OAG) (soutien de la paix, concept de la guerre à trois volets, etc.) auxquelles le Canada et les pays alliés participent de plus en plus, exige que les officiers des Forces canadiennes (FC) fasses appel à des compétences supérieures en matière de prise de décisions dynamique à un niveau sans précédent, en particulier aux plans opérationnel et stratégique (Rehak, Lamoureux, & Bos, 2006). Le caractère complexe et dynamique de ces divers types d'opérations pose des problèmes cognitifs particuliers au processus de prise de décisions que l'instruction actuelle des commandants militaires ne traite pas directement. RDDC Toronto est donc à la recherche de techniques d'instruction qui permettront de former les commandants et les membres d'état-major des Forces canadiennes à la prise de décisions dans des environnements complexes et dynamiques (12sk). Le présent compte rendu renferme un aperçu de la documentation sur la PDD et sur les modèles mentaux associés à la PDD.

La PDD implique la participation (1) d'un décideur, (2) dans un environnement complexe, (3) qui tente d'exécuter une ou plusieurs tâches. La PDD est nécessaire dans des environnements complexes où le risque est élevé. Elle implique l'exécution de tâches requérant des étapes multiples, pour lesquelles le temps est important, qui sont interdépendantes et qui exercent une influence sur le milieu environnant, tout en étant influencées par lui. La prise de décisions dynamique a été explorée à partir de différents points de vue, notamment la théorie des systèmes, la psychologie et la théorie de contrôle dans le domaine de l'ingénierie. Ces perspectives mettent l'accent, à divers degrés, sur différents aspects de la PDD. Du point de vue de la théorie des systèmes par exemple, l'accent porte sur la création d'analogies qui tentent de simuler les processus que les gens utilisent pour gérer des systèmes complexes. De plus, ces analogies représentent une façon d'aider les gens à former des modèles plus précis du système. Par ailleurs, du point de vue psychologique, l'accent porte sur les ensembles de choix que les gens peuvent faire lorsqu'ils essaient de prendre des décisions complexes. La théorie du contrôle met principalement l'accent sur le rôle de la rétroaction dans la gestion d'un système complexe. Une hypothèse est commune à toutes ces approches : qu'il s'agisse de former des modèles de systèmes complexes ou de prendre des décisions intuitives à partir de très peu de renseignements, les gens ont tendance à développer une certaine forme de modèle mental pour effectuer une PDD.

De façon générale, on peut décrire les modèles mentaux comme des représentations mentales de notre monde. Bien qu'il n'y ait aucun consensus sur la définition des modèles mentaux, ces derniers sont généralement reconnus pour être associés à trois fonctions clés : décrire, prédire et expliquer le monde qui nous entoure. Le présent rapport avait pour but de découvrir de quelle façon les modèles mentaux sont compris parmi toute une gamme de points de vue pertinents. Du point de vue de la logique des propositions, on allègue que le raisonnement dépend de l'imagination des possibilités compatibles avec les prémisses et des conclusions que l'on tire de ces représentations mentales. Il y a cependant un certain nombre de facteurs qui limitent l'application de modèles propositionnels à la prise de décisions dynamique (p. ex., attention portée à un très petit sous-ensemble de tâches de raisonnement impliquant des concepts statiques finis, absence d'interaction entre les répercussions des décideurs sur la tâche ou l'environnement). La perspective des systèmes physiques définit les modèles mentaux comme étant les modèles que les gens utilisent dans leur raisonnement sur le monde physique. Toutefois, la documentation sur les systèmes physiques soulève un certain nombre de questions relatives à la capacité des modèles mentaux d'appuyer la PDD (p. ex., nous ne savons pas de quelle façon ces modèles mentaux sont créés ou

fonctionnent dans le contexte de la PDD). La perspective du modèle de situation définit un modèle de situation comme étant la représentation dynamique de la connaissance et de la compréhension qu’a une personne de *l’état actuel* d’un système, alors que la perspective de la dynamique d’un système décrit les modèles mentaux comme étant la représentation conceptuelle interne d’un système externe. Dans la présente analyse, on a trouvé peu de similitudes dans les descriptions des modèles mentaux entre les domaines examinés. La conclusion met en lumière les difficultés à comprendre les modèles mentaux déjà décrits dans la documentation sur les modèles mentaux (p. ex., le manque d’une définition claire, la difficulté à mesurer les modèles mentaux). En outre, on a découvert que des modèles mentaux étaient sujets à une variété de lacunes ayant une influence sur leur exactitude (p. ex., capacité cognitive limitée, liens causals erronés fondés sur des renseignements incomplets, erreurs systémiques).

On a évalué jusqu’à quel point la PDD pouvait être appuyée par chacune des approches uniques à la compréhension des modèles mentaux. En ce qui a trait aux modèles opérationnels, il a été difficile de trouver des symétries substantielles entre cette perspective de modèles mentaux et la PDD. De la même façon, une partie limitée de la documentation portant sur les modèles mentaux des systèmes physiques pouvait être liée adéquatement à la PDD. De plus, certaines incohérences dans la définition des modèles mentaux de la dynamique des systèmes rendent difficile la compréhension claire du rôle des modèles mentaux dans la PDD. On a estimé que la perspective du modèle de situation était favorable pour appuyer la PDD étant donné que ces modèles permettent à un décideur d’intégrer les changements d’un système à son modèle de situation de manière à lui fournir une vision précise et à jour de l’état et de la fonction du système. Toutefois, la recherche laisse entendre que les gens ne sont pas particulièrement efficaces pour créer des modèles de situation justes.

Le compte rendu a également exploré jusqu’à quel point l’utilisation des modèles mentaux appuie le processus de PDD. En ce qui a trait aux décideurs dynamiques, la documentation sur les modèles mentaux ne renferme que de vagues descriptions des processus exacts qu’ils utilisent. En outre, la documentation signale un certain nombre de restrictions empêchant les décideurs de former et d’appliquer des modèles mentaux, notamment des restrictions cognitives, l’effort mental, les heuristiques et les biais. De la même manière, il est peu probable que le contexte de la PDD (complexité, rétroaction) et les tâches de la PDD appuient l’utilisation de modèles mentaux pour prendre des décisions. Cela ne signifie cependant pas que les modèles mentaux ne peuvent pas être utiles, mais simplement que les limites des modèles formés, quels qu’ils soient, devraient être reconnues.

L’examen se termine avec deux tableaux qui résument les lacunes de la documentation. Le premier tableau passe en revue la recherche des modèles mentaux à améliorer pour servir la PDD et le deuxième tableau met en relief les questions générales relatives à la recherche sur les modèles mentaux qui devraient être traitées.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Background

The complex and dynamic nature of military operations in which Canada and allied nations are increasingly involved requires Canadian Forces (CF) officers to call upon high-level dynamic decision-making (DDM) skills to an unprecedented degree, especially at the strategic and operational levels (Rehak, Lamoureux, & Bos, 2006). The complex and dynamic nature of these various types of operations pose specific cognitive challenges on the decision-making process that the current training regimen of military commanders does not directly address. Therefore, DRDC Toronto is interested in researching training techniques to prepare Canadian Forces (CF) commanders and staff for decision-making in such complex and dynamic environments.

Dynamic decision-making (DDM) generally refers to situations that require a series of interrelated decisions made in real time with the aim of controlling or influencing a situation. This is in contrast with the more “static” decision-making approach traditionally researched in psychology. In DDM, the state of the problem changes continuously, both autonomously and as a consequence of the decision-maker’s actions, and the decision-making environment is opaque (i.e., it is not possible for a decision maker to know all aspects or variables of the environment, and therefore some characteristics of the system must be inferred) (Brehmer, 1992).

Much of the research conducted on DDM assumes that mental models and mental simulation skills, or at least recognition processes, are crucial to successful DDM (see, e.g., Brehmer, 1990; Gonzalez, Lerch, & Lebiere, 2003). However, little scientific publications on DDM make reference to any psychological theories of mental models. Furthermore the DDM literature does not provide much information on the cognitive mechanisms that would underlie DDM. This dearth is problematic, especially as accounts of mental models vary in the extent to which mental models rely on visual representation – on a continuum from purely visual images to purely propositional logic. Although it is difficult to see how purely proposition-based mental models might be suited to DDM, it raises the question of what form do mental models take in DDM, and what role do they play in the DDM process?

In contrast to psychology, the cognitive engineering approach to supporting DDM has relied on the system dynamics approach to modeling complex systems. This approach assumes that presenting models of the dynamics of typical systems (i.e., the evolution over time of the set of variables that describe it) to decision makers will help them improve their DDM skills. These models might be interactive simulations (microworlds) or simply diagrams of the system. The underlying hypothesis of this approach is that presenting the decision makers with such models will improve their mental model of the system and its dynamics. Again, despite such a reliance on the concept of mental model, very little reference is made to the literature on mental models. In fact some research in the system dynamics field has identified a lack of consensus among systems dynamics practitioners as to what mental models are (Doyle & Ford, 1998).

The objective of this work is to understand what kinds of mental models or representations are involved in DDM, and the role they play in the DDM process,

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1.2 Scope and objectives

The overall aim of this work/project is to review literature on mental models and DDM in order to better understand the form that mental models take in DDM and the role that they play in the DDM process. More specifically, the objectives are:

1. To review relevant DDM literature.
2. To review the literature on mental models as it relates to DDM.
3. To determine gaps, if any, in the literature on mental models regarding DDM.
4. To construct (or build upon an existing) conceptual framework for relating mental models to DDM, guiding areas for future research on mental models relative to DDM, and identifying constraints and implications for DDM training.

1.3 Outline of report

This report provides a review of relevant DDM literature and mental models literature as it relates to DDM.

This report has six main sections:

1. Introduction;
2. Method;
3. Dynamic Decision-Making;
4. Mental Models;
5. Mental Models and Dynamic Decision-making; and
6. Future Research Recommendations based on Gaps in the Literature.

These sections encapsulate the work items described in the Statement of Work (SOW).

2. Method

2.1 Literature Reviews

A structured process was applied in conducting the literature review. It included finding the relevant articles (either through their provision by the SA or through extensive searching), filtering relevant articles, reviewing the articles and then performing the final analysis and synchronization of the status of the literature. These steps were conducted twice, once focusing on dynamic decision making and once focusing on mental models. More details on finding and filtering the articles can be found below.

2.1.1 Dynamic Decision-making

The first part of the literature review looked to understand and document the characteristics and research status of DDM. After discussions with the SA at the start-up meeting, it was agreed that the SA would provide HSI® with the appropriate articles to be reviewed for DDM. In total, the SA provided HSI® with 19 articles on DDM to be reviewed. This list was augmented with an additional three articles that were found while conducting the searches detailed below.

2.1.2 Mental Models in Dynamic Decision-making

Building on the previous section, the second phase of the project looked at mental models. This included literature on mental models in general as well as mental models applied in DDM. They keywords used in the search can be found below in Table 1.

Table 1: Keywords

Core Concept	Primary Keywords	Secondary Keywords
Decision-making	Reasoning, judgement, problem solving, intuitive, rational, naturalistic,	Creativity, deductive, inductive, inference, analytic, counter-factual reasoning
Dynamic Decision-making	risk, complexity, uncertainty, ambiguity, problem space	
Systems theory	System dynamics, complex systems, D3M (distributed dynamic decision-making)	Nonlinearity, stock and flow, feedback loops, causal loop, emergence, emergent behaviour
Contexts	Military, crisis, operational, strategic, command and control, C2, effects based operations, 2nd/3rd order effects	Uncertain, critical, pressure, risk
Mental Models	Cognitive mechanisms, probabilistic information processing, cognitive model, representations, mental processes, logic	Psychological theories, stock and flow, framework, learning theory, mental representation, mental simulation
	Physical systems	
	Situation models	
	Isomorphism	
Cognitive	mental, knowledge, intellectual, ability	
	sensory, perception, attention, workload	
	learning	training
	memory	forgetting, retention, recall, maintenance
	language, communication	

In conducting the search for mental models articles, the primary keywords were searched independently and were paired with “mental models”.

2.1.2.1 Databases

A variety of databases were searched. These are summarized below in Table 2.

Table 2: Databases searched

Database	Description
PsycINFO	The PsycINFO database is a collection of electronically stored bibliographic references, often with abstracts or summaries, to psychological literature from the 1800s to the present. The available literature includes material published in 50 countries, but is all presented in English. Books and chapters published worldwide are also covered in the database, as well as technical reports and dissertations from the last several decades.
NTIS	NTIS is an agency for the U.S. Department of Commerce's Technology Administration. It is the official source for government sponsored U.S. and worldwide scientific, technical, engineering and business related information. The 400,000 article database can be searched for free at the www.ntis.gov. Articles can be purchased from NTIS at costs depending on the length of the article.
CISTI	CISTI stands for the Canada Institute for Scientific and Technical Information. It is the library for the National Research Council of Canada and a world source for information in science, technology, engineering and medicine. The database is searchable on-line at cat.cisti.nrc.ca. Articles can be ordered from CISTI for a fee of approximately $12.
STINET	STINET is a publicly-available database (stinet.dtic.mil) which provides access to citations of documents such as: unclassified unlimited documents that have been entered into the Defence Technology Technical Reports Collection (e.g., dissertations from the Naval Postgraduate School), the Air University Library Index to Military Periodicals, Staff College Automated Military Periodical Index, Department of Defense Index to Specifications and Standards, and Research and Development Descriptive Summaries. The full-text electronic versions of many of these articles are also available from this database.
Google Scholar	The World Wide Web was searched using the Google Scholar search engines (scholar.google.com).
DRDC Research Reports	DRDC Defence Research Reports is a database of scientific and technical research produced over the past 6- years by and for the Defence Research & Development Canada. It is available online at pubs.drdc-rddc.gc.ca/pubdocs/pcow1_e.html.

2.1.2.2 Search strategy

To maintain a record of the process, the following information was documented in a spreadsheet throughout the search process:

- Database searched (e.g., Psych Info);
- Keyword combination (e.g., Non intrusive AND attenti*);
- Number of hits;
- Number of possible articles;
- Articles downloaded; and
- Articles/books that require purchase.

2.1.2.3 Selection and review of articles

HSI identified 41 possible articles for the mental models review. These articles were then narrowed down to 18 articles, which were presented to the SA. Through further iterations of searching and filtering, five of the original 18 articles presented to the SA were removed from the list as an additional 13 articles were found to be more relevant. We were also asked to use one specific article from Annex A to the Statement of Work. In total, 34 articles were reviewed for the mental models literature section.

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3. Dynamic Decision-making

3.1 Defining Dynamic Decision-making

There are four key elements that define dynamic decision-making (DDM) (Brehmer & Allard, 1991; Busemeyer, 1999; Clancy, Elliott, Ley, Omodei, Wearing, McLennen & Thorsteinsson, 2003; Fu & Gonzalez 2006):

- There are a series of decisions;
- These decisions are interdependent;
- The environment changes both autonomously and as a function of the decision maker's actions; and,
- Timing is a key element, where decision makers have little control over exactly when dynamic decisions must be made (Brehmer, 2000).

These decisions are not made autonomously, they must be made by decision makers. Further, the decision maker is acting out of desire to accomplish something – to reach a goal or complete a task. This task is being attempted within the confines of its environment, upon which the decision maker has little or no control. Thusly, breaking DDM into its constituent parts, DDM involves (1) decision maker(s) (2) in a complex environment (3) attempting to accomplish one or more tasks. Characteristics of each of these three constituent parts and elaboration of the key elements of DDM are discussed in the upcoming sections.

3.1.1 Decision Maker

At the centre of any dynamic decision-making event is the decision maker. Decision-making power can be centralized to one person or may be distributed to many people. A main aim of dynamic decision makers is to gain control over their task environment (Clancy et al., 2003). This is typically done through making a series of decisions (Brehmer & Allard, 1991) rather than making a single choice. The key issue in controlling the task, moreover, requires the decision maker to sustain a workable compromise between the demands of the task and the need to conserve one's cognitive resources (Brehmer, 2000). To gain control, successful dynamic decision makers must handle two types of problems (Brehmer, 2000). That is, dynamic decision makers must handle the "core" decision task, and must also control the overall decision situation. "Core" decisions are required to control the aspects of the situation that are of concern (Brehmer, 2000). For example, the core decision task in military command and control is to defeat the adversary. The decision maker(s) must recognize the relationship between the characteristics of the controlling process and the controlled processes. In fire fighting, for example, the fire is seen as a process with temporal characteristics (controlling process) and the mechanisms available to the fire chief to fight the fire are also seen as a process (controlled process). The tactical methods used by the fire chief to fight the fire are based on the relationship between these two processes. Complicating this relationship is the time-dependent nature of their decisions (e.g., it takes time for decisions to take effect; the magnitude of effect varies over time). Tactical problems are incurred when the controlled process changes faster than the controlling process can have an effect.

In addition to handling the "core" decision tasks, decision makers must also control the overall decision situation to avoid overload and to remain capable of making core decisions (Brehmer, 2000). Given the complexity of the situations within which DDM is required, becoming distracted by secondary factors could lead to overload and the inability to focus on the most critical elements. A key part of controlling the decision situation, then, may involve making determinations about how to balance the effects of core decision tasks on other competing goals. In fighting a fire, for example, Brehmer (2000) argues that the fire chief's core task is to control the fire. On the other hand, the broad situation is also likely to introduce a number of secondary demands, such as the need to control the gathering crowd, or the need to coordinate the efforts of multiple players working to diffuse the situation. These secondary characteristics of the situation may challenge the fire chief's ability to give adequate attention to the most critical tasks.

3.1.2 DDM Tasks

Dynamic decision-making occurs across a broad spectrum of tasks including fire fighting, military combat, search and rescue, and medical emergencies. There are a number of key features that characterize dynamic decision-making tasks, which are outlined below.

Interdependence: DDM tasks are highly complex because they are typically composed of multiple interdependent components that can influence the system as a whole as well as each other (Brehmer, 1990). Earlier decisions can constrain later decisions, and limit the ones that follow.

Uncertainty. DDM tasks are highly uncertain for a number of reasons (Clancy et al., 2003). Uncertainty can be due to the fact that changes in the DDM system occur both autonomously and as a result of previous decisions or actions performed in the system. Another factor adding to uncertainty in dynamic decision tasks is the invisibility of some aspects of the system (Gonzalez, 2005). This opaqueness (as termed by Brehmer, 2000), refers to a "lack of transparency about the decision situation" (p. 239). Opaqueness can result from a lack of information about the status of the DDM task, as well from as a lack of information regarding the relationship between the processes to be controlled (Brehmer, 2000; Gonzalez, Lerch, & Lebiere, 2003). Feedbacks delays are an important cause of opaqueness.

Time. Time is a key element of dynamic decision-making (Brehmer & Allard, 1991) because DDM focuses on tasks that must be completed in real-time. The implication of this is that the decision maker does not have sole control over when decisions need to be made (e.g., does not control the pace and tempo of decisions). As Brehmer (1990, p. 263) argues, "…the world will never stop and wait for him to make his decisions". Dynamic decisions sometimes have windows of opportunity within which actions need to be initiated for optimal decisions to be made. Outside of that window, the environment, situation, and/or task requirements can change and the decision action may no longer be applicable. Decision-actions must be made not only at the most opportune time, but also in the correct order (Brehmer, 1992). Time is also critical in DDM because each task may be unique in terms of the critical time scale in play. When fighting a large fire, for example, the most immediate time problem and direct effects may be obvious, but other factors could also become time critical.

High Levels of Risk. There is an element of risk associated with decision makers' actions (Clancy et al., 2003). In dynamic decision-making contexts, the stakes and the cost of making a wrong decision can have serious consequences. For example, a firechief who sends all available assets to one location will have no assets available to send out should another emergency arise elsewhere (Brehmer, 2000).

Ill-Structured Problems. DDM problems are rarely well-defined and the decision maker must struggle to identify the key features of the problem (Clancy et al., 2003). This can be difficult as decision makers often have multiple goals and the priorities of these goals can change as the situation develops (Flin, 1996; as cited in Clancy et al., 2003).

3.1.3 DDM Environments

When trying to make dynamic decisions, it is vital to understand to the best of one's ability the environment in which the decisions are made. Brehmer and Allard (1991) suggest that dynamic decision contexts can be characterized as involving complexity, rate of change, relations, delays, feedback, and distribution of decision-making capacity.

Complexity. DDM environments are highly complex. Although there is no clear operationalization of complexity, Brehmer and Allard (1991) define the complexity in a given situation as relative to the capacity of a human to control the number of processes, goals, action alternatives and side effects of the system. In the case of fire fighting, then, complexity would emerge as a product of the number of fires in play, the varying goals that are in play (i.e., some fires may be more critical than others), the number of resources and options available, and the secondary effects of putting out the fires (e.g., impact on the environment). Feedback within the system can also add another source of complexity (Hsiao & Richardson, 1999). Positive gains, negative feedback loops, and delayed feedback can easily be mismanaged, misinterpreted, or even ignored, which adds another layer of difficulty to already cognitively taxing decision-making (Hsiao & Richardson, 1999). Delays in any link of the chain can add a layer of complexity that requires decision makers to account for lags in sending and receiving information and initiating, engaging, and completing decision-actions.

Rate of change. Rate of change refers to how quickly the processes to be controlled change. Changes can be very slow (e.g., controlling a country's economy) or very fast (e.g., performing a low-level fighter jet attack).

Relation between the characteristics of the process to be controlled and those of the control processes. DDM requires the decision maker to control a time-dependent process. However, the means to control this process are also dynamic (e.g., it takes time for decisions to take effect; the magnitude of effect varies over time). If the process under control changes, then the effectiveness of the actions used to control the process will also change. Brehmer and Allard (1991) again use a fire fighting example – if the delay in getting fire fighting units (FFU) to the scene is not figured into the estimate of how many units will be required, the fire could be larger when these FFU actually reach the fire, making it impossible to control the situation.

Feedback Delays. Delays refer to when the transmission of information or energy slows down or lags behind in the dynamic decision system. Delays can be quite complex because they may occur in different locations in the system. Within a fire fighting team, for example, delays could be experienced getting commands to the FFUs, in the FFUs actually responding to the delays.

Quality of feedback information. The quality of the information about the progress of the task can vary, which can be a source of uncertainty for dynamic decision makers. This variance can be a product of the information systems used to transmit information, or of the quality of the reports sent by other team members.

Distribution of decision-making capacity. Decision-making power can be centralized to one person or be distributed to many people. How decision-making capacity is distributed is likely to play a

key role in how DDM occurs. If the working "model" of the system does not incorporate the delays inherent within a centralized system, this model will not be helpful because it will be out of date.

3.2 Domain related perspectives on DDM

DDM has been approached and studied from a number of different perspectives. These perspectives include system dynamics, psychology and engineering science. Each of these perspectives views DDM uniquely and emphasizes distinct aspects of the DDM process. Examples of these perspectives are discussed in more detail in the sections that follow.

3.2.1 System Dynamics: Stock & Flow

The system dynamics approach aims to understand the behaviour of complex systems over time (http://en.wikipedia.org/wiki/System_dynamics). Systems theory is often distinguished by its focus on nonlinearity, and its use of internal feedback loops, time delays that affect the entire system, as well as the use of stocks and flows. Several thinking skills have also been identified as critical within a systems perspective (Sweeney and Sterman, 2000), including the ability to:

- Understand how behavior of the system arises from the integration of its agents over time (i.e., dynamic complexity);
- Discover and represent feedback processes (positive and negative) hypothesized to underlie observed patterns of system behavior;
- Identify stock and flow relationships;
- Recognize delays and understand their impact;
- Identify nonlinearities; and
- Recognize and challenge the boundaries of mental (and formal) models.

According to Elg (1996), system dynamics offers a framework for understanding DDM and provides ideas on how to improve learning in and about complex dynamic systems. System dynamics provides a way for us to improve our understanding of the systems we want to control. Given the complexity and emphasis on "flow" in DDM, then, it is perhaps unsurprising that systems theory has been frequently used to understand and explore DDM.

System dynamics has two general goals (Elg, 1996). The first goal is to understand complex, dynamic systems by modeling and analyzing the system. This is achieved by conducting empirical and theoretical studies on real life problems and implementing the results of the studies in a simulation model for analysis. The second goal is to improve system reasoning abilities and to develop the ability to understand, conceptualize and build models of systems. In DDM tasks, these goals help researchers understand and improve DDM behaviours from a holistic, systemic perspective.

A system dynamics approach to measuring DDM often uses stock and flow scenarios as frameworks for investigating complex systems. Many stock and flow scenarios will be presented in this section in the form of a supply chain system microworlds as used by Cronin and Gonzalez (2007), Fu and Gonzalez (2006), and Sterman and Diehl (1993) (for more on Microworlds see section 3.3).

Sterman (2002; as cited in Cronin & Gonzalez, 2007) suggests that people have problems understanding system dynamics. It is suggested that such difficulties are because we have a poor understanding of the building blocks of system dynamics, including stocks, flows and time delays (Cronin and Gonzalez, 2007). Cronin and Gonzalez (2007) were interested in understanding the cognitive functions that explain why people misunderstand the relationship between stocks and flows. They conducted a series of three studies to test whether the familiarity of the dynamic system, cognitive effort, computational difficulty, and/or graphical features were responsible.

The first study explored possible reasons why participants in previous research had difficulty understanding stocks and flows. They looked at two possibilities: 1) the cover stories of previous studies did not highlight the "stocks" portion of the model resulting in an incorrect mental model of the system, and 2) participants in previous studies used little effort to think about the problem. The study asked university participants to look at different graphs and describe the amounts and movements of stocks. The researchers found no significant differences between groups as the result of two different cover stories (one that highlighted the stocks portion of the model and one that did not) or as a product of varying levels of thinking effort. This finding, Cronin and Gonzalez argue, lends support to the idea that people may not develop sufficient mental models or heuristics necessary to adequately support DDM in a dynamic stock and flow environment.

The next two studies investigated the role of visual form in constructing inappropriate representations of problems that may lead to poor performance. Participants were asked to use information from a number of visually different graphs. The results of these studies led Cronin and Gonzalez (2007) to conclude that the visual representation of dynamic systems can influence people's understanding of the relationship between stocks and flows. That is, graphical depictions direct attention to some things but not others. This suggests that the visual representation of the dynamic system, or how the decision maker interprets the system representation, may have a significant role in the design of the heuristics and mental models used in DDM.

Fu and Gonzalez (2006) propose that heuristics used may produce stable behaviour in one setting and oscillation in another solely as a function of the feedback structure in which it is embedded. They suggest that heuristics may not be adequate to support the DDM task. In some cases where people may be successful in controlling the system, success may be a function of an incidental match between the decision maker's behaviour and what the system requires, rather than a successful match of conscious effort on the part of the decision maker (Fu & Gonzalez, 2006).

In order to investigate this, Fu and Gonzalez (2006) conducted research exploring two questions related to learning of temporal dynamics in dynamic decision-making. The first question related to what information is utilized and how this information changes with experience. The second question explored what different strategies are dominant when comparing learning behaviour in static versus dynamic decision-making situations.

Fu and Gonzalez (2006) used a simplified supply chain system in a microworld platform called The Beer Game. In this game, a single retailer supplies beer to the consumer, a single wholesaler supplies beer to the retailer, the distributor supplies beer to the wholesaler, and the factory to brews and supplies beer to distributor. The object of the game is to minimize inventory and avoid backorder while maximizing profit. Delays are introduced into the system in order to manipulate the complexity of the system and encourage changes in the strategies used to make decisions in this dynamic environment.

Fu and Gonzalez (2006) showed that initially participants failed to sufficiently change their decision-making strategies. They tended to ignore temporal dynamics of the system and

consequently underutilize information that indirectly influenced the outcome of decisions (Fu & Gonzalez, 2006). With practice, however, participants learned to use relevant supply line information to anticipate customer demand and learn to ignore irrelevant information. This learning effect was not found by Sterman and Diehl (1993), who also used a systems dynamic approach to investigate the effects of time delays and feedback processes on DDM performance.

Using a microenvironment of a managing firm, Sterman and Diehl (1993) found no learning effects based on the time taken to act on the system when a decision-action was required. Two main sources of underperformance were identified. First, people would employ the correct model, but apply it inconsistently. This mistake is fueled by the failure to properly account for the time delays or feedback loops (Sterman & Diehl, 1993). Second, an incorrect model was consistently employed. Specifically, it seemed that participants did not properly account for the importance of relevant information (mainly underweighting of inventory, future production, and stages of the supply line) (Sterman & Diehl, 1993).

Though incorrect models may be employed, it was demonstrated by Fu and Gonzalez (2006) that people do possess the cognitive machinery necessary to deal with DDM tasks. And, with extended practice and coaching, people are capable of controlling complex, dynamic systems. Fu and Gonzalez (2006) provided more evidence that the relevance of information directly impacts performance. When participants were presented with only the relevant and necessary information within the system, performance was better compared to those who were provided with both relevant and irrelevant information where no distinction was made between the two. This suggests that the absence of irrelevant information helps participants to learn temporal dynamics of system and result in better performance when controlling DDM in a microworld platform in stock and flow environments.

Results from both studies suggest that, at least initially, people have trouble dealing with long time delays between actions and feedback (in supply line) (Fu & Gonzalez, 2006; Sterman & Diehl, 1993). This supports the misperception of feedback (MOF) hypothesis defined by Sterman & Diehl (1993) that states people have an ‘open-loop’ view of causality; they fail to account for delays between action and response, and acquisition of information; ignore feedback processes; do not sufficiently understand stocks and flows; and are “insensitive to nonlinear complexities in the system that may change the relevance of different feedback loops as a system evolves” (p. 1).

The studies explored in this section show how a systems dynamic approach allows dynamic decision-making to be experimentally manipulated in realistic real-world stock and flow environments. System dynamics research has helped to clarify and understand some of the strategies and processes people use when faced with complex situations involving different sources of visual representation of the system (Cronin & Gonzalez, 2007); delayed feedback (Sterman & Diehl, 2003; Fu & Gonzalez, 2006); varying amounts and types of relevant or irrelevant information (Fu & Gonzalez, 2006); and sources of underperformance (Sterman & Diehl, 2003). Systems dynamics research may be particularly useful in trying to identify mental models and heuristics used in DDM as there has been a substantial “…portion of [system dynamics] research effort to developing a wide variety of techniques and procedures for eliciting, representing, and mapping mental models to aid model building’ (Hall, Aitchison & Kocay, 1994; as cited in Doyle & Ford, 1998, p.3). An assumption that permeates throughout system dynamics is that mental models are created, modified and used to mediate all DDM. A major problem is that definitions of mental models are typically general, vague, and authors often disagree (Doyle & Ford, 1998).

The system dynamics approach to DDM has limitations that confine the study of DDM to contexts where it is assumed people have a general knowledge and understanding of the system, its

components (e.g., key information about demands and supply is known), its structure, and function; the ability to understand, analyze, and create mental models about the system; and that these assumptions are influenced by reasoning ability and have important impact on DDM performance. Though this approach is able to provide a method of understanding and experimentally examining DDM in certain environments, this approach may not be equally applicable to the wide range of real-world scenarios where DDM is found.

3.2.2 Psychology – DDM as Choice

Psychology has also been active in recent decades working to understand dynamic decision-making. It is important to note that this has not always been the case, however. In fact, as late as 1990, Brehmer (1990, p. 264) argued that even though examples of "real-life, dynamic tasks are not hard to find", he lamented that these tasks "…have received little attention from psychologists, except in the form of a few scattered studies of process-control tasks" (Brehmer, 1990, p. 264). Brehmer (2000) argued that there were two possible reasons for psychology's relative neglect of DDM. First, he argued that the research methodologies needed to explore it were lacking, as traditional psychological research relied on paper-and-pencil approaches. Second, he argued that the normative models typically used in behaviour decision research (e.g., Slovic, Fischoff & Lichtenstein, 1977) could not adequately capture dynamic decision-making.

These analytic theories of decision-making emphasized normative and rational approaches, which tended to argue that people proceed progressively through a rational process of problem-solving when presented with issues in complex situations. According to Brehmer and Allard (1991, p.320), "a decision problem is defined in terms of a set of possible actions, connected to a set of possible consequences of these actions by means of probabilities. The decision maker's task is to select the option that leads to the best outcome, usually defined as the alternative with the highest expected value. Thus, decision-making is seen as a matter of resolving a choice dilemma." Indeed, these types of approaches to understanding decision-making have often portrayed it as providing "an array of well-specified alternatives on the basis of some form of a) subjective expected probability or b) a utility maximized algorithm" (Clancy et al., 2003, p. 588). This research has also often used highly artificial tasks and has often involved trivial rather than consequential outcomes as the result of the decision-making process (Clancy et al., 2003).

As decision-making theory progressed, however, it began to emphasize more complex environments, and extended beyond the need to make a single "maximal return" choice to the need to control multiple sequences of interrelated decisions. The evolving descriptions of decision-making focused not on how people should make complex decisions, but on how they actually did make these decisions in the real world. In keeping with this trend away from the purely rational forms of decision-making, a considerable body of work has explored more naturalistic and intuitive forms of decision-making.

Several different lines of research have generated an interest in more intuitive models of conventional decision-making as an alternative to the strict rational models. Known generally as Naturalistic Decision-making (NDM), this approach has been defined as the study of how people use their *experience* to make decisions in the real world (Zsambok & Klein, 1997; cited in Pliske & Klein, 2003; Bakken & Vamraak, 2003), often under time pressure, risk, and uncertainty. NDM diverges from more traditional approaches of decision-making because it strives to consider decisions in context rich settings, people with domain experience, descriptions of decision-making strategies, and pre-choice processes such as the development of situation awareness (Zsambok, 1997; cited in Pliske & Klein, 2003). In situations of limited time, high risk and a great deal of

uncertainty, searching for the optimum solution to a difficult decision (as prescribed by normative models of decision-making) might actually hinder the process as opposed to improving it. This work emphasizes the notion that decisions (particularly those in complex situations) are typically not made through the careful sifting and rational weighting of alternatives, but that factors such as accumulated expertise and pattern matching help to guide intuitive decisions. Accepting that sub-optimal solutions may have benefits is in contrast to the system dynamics perspective that preferred to always compare dynamic decisions to the optimal solution.

This suggests that more complex models of decision-making might be necessary to capture complex and dynamic processes. One issue that might promote effectiveness would be experience in the target domain. In military operations, for example, commanders are continuously receiving status information and, on the basis of that information, managing their resources. Once the directives are acted upon, subordinates will report back with outcomes and new status report. This cycle continues for the duration of the operation. The cyclical nature of military operations suggests that military planners would be better at making intuitive judgments than most decision makers. However, there is also evidence that even more complex models may not necessarily be wholly adequate. Baaken and Vamraak (2003) hypothesized that even military planners would face the same challenges as other people making intuitive judgments. To test this hypothesis, they had seven highly educated defence analysts conduct a "Peace Support" planning task focusing on the dynamic interrelations between budget allocations and cost of operations (initial purchases and running sustenance). Included in the scenario was also a one-time budget increase that could lead to a short-term performance boost as well as a long-term penalty. Each participant was provided with a task description and an answer grid. They were asked to complete the answer grid with a hand drawn sketch of the estimated total effect curve between the time of starting extra funding and 40 days ahead in the simulation.

Baaken and Vamraak (2003) found that the participants were consistently over-optimistic and demonstrated only a partial understanding of the dynamics generated by the logistics chain structure. Participants were unable to reproduce the cyclic performance resulting from the budget increase. The hand drawn graphs resembled a "plain" budget profile stretched out in time. Subsequently, Bakken and Vamraak (2003) concluded that intuition alone is not always an adequate guide for dynamic decision-making.

Other psychological approaches to understanding DDM have focused on cognitive processes such as learning, planning, and problem-solving. Busemeyer (1999) suggests that learning processes may account for much of the variance seen in human performance on dynamic decision-making tasks. For example, instance or exemplar-based models assume that actions leading to successful outcomes are stored together in memory, to be retrieved when the decision maker encounters similar situations. Gonzalez et al. (2003) propose a learning theory of DDM called "instance based learning theory" (IBLT). IBLT proposes that people have instance-action based constructs that are stored and linked together in memory. These coupled constructs are retrieved on the basis of similarity to a current situation. When the instance is matched, the behaviour is recognized as a viable action to be performed in the current situation. As the instance based repertoire is accumulated, stored, and improved upon with experience, learning can take place. In DDM people learn by accumulation, recognition, and refinement of instances (information about the decision-making situation, action, result of decision) (Gonzalez et al., 2003)

A variety of DDM research reveals much about the flaws in people's ability to manage dynamic complexity (Sterman & Diehl, 1993). Sterman (1987) conducted a study that ran participants through a DDM experiment and then modeled their responses based on two known heuristics (i.e.,

anchoring and adjustment heuristics). The system chosen for the experiment was called the multiplier-accelerator model of capital investment. Participants in this study included both students and economic professionals knowledgeable about economic and control theory. Despite only a single simple system input change, only 8% of the participants were able to re-establish equilibrium before the end of the simulation. A model of the decision responses based on the anchoring and adjustment heuristic proved to effectively mimic the DDM patterns of participants. This is consistent with Elg (1996) who noted that when identifying problems, people conceptualize their environments and make conclusions according to their perceived state of the situation.

After further studies showing consistency in participants' sub-optimal performance, Sterman and Diehl (1993) postulate possible causes. They attribute this poor performance to two possible reasons. First, they argue that participants may be unsuccessful due to the fact that they do not understand the system because of its complexity, and thus use minimum effort to maintain a minimum level of control. Second, they argue that participants may suffer from two types of misperceptions of feedback. The first misperception may be that that people are insufficiently aware of the structure of the feedback system. Because of this, they tend to use a 'hands-off' strategy failing to understand how their actions influence the system. The second feedback problem is that people are unable to account for delays and feedback effects. This could the result of either faulty mental models that are oversimplified for complex control tasks, or because people have a poor ability to correctly infer the behaviors necessary to control complex feedback systems.

In general, however, it is very difficult to truly disentangle conceptualizations of DDM from the psychological domain with those from the system dynamics domain, and there seems to be a good deal of overlap in these approaches to DDM. Perhaps the best way to distinguish them is by examining what processes they emphasize. From the psychological perspective, for example, processes such as decision-making, learning, planning and problem solving are clearly relevant to DDM. However, from the systems perspective, the focus is not on these psychological processes per se, but on the instantiation of these processes using system analogies (e.g., stock and flow diagrams). From the psychological perspective, then, the choices of the individual within the DDM situation may be the focus, whereas the system analogy aims to instantiate the mental process in an observable way.

3.2.3 Control Theory – DDM as Control

In a 1990 article by Brehmer, it is argued that conventional psychological approaches may be inadequate for capturing DDM, in part because these approaches had been based in the normative models used in behavioural decision research. In attempting to find another framework for conceptualizing DDM, Brehmer (1990) argues that control theory might be a helpful approach.

Control theory is a branch of engineering that deals with the behaviour of dynamic systems, and mathematically models the ways one process controls another process (Brehmer, 2000). Given that the objective of dynamic decision-making is to achieve control over some aspect of the environment (i.e., decisions are made to achieve a desired state of affairs or to keep a system in a desired state), Brehmer (1992, 2000; Brehmer & Allard, 1991) suggested that control theory could be used as a framework for guiding DDM research. From a psychological perspective, DDM is defined in terms of resolving a choice dilemma, whereas from a control theory view, DDM is defined as "…the process of achieving control over a system in order to produce a desired outcome" (Brehmer, 1990, p. 265). That is, control theory was argued to be helpful in understanding DDM because it specifies the general conditions required to control a system. These general conditions are that:

- There must be a goal (goal condition).
- It must be possible to ascertain the state of the system to be controlled (observability condition).
- It must be possible to change the state of the system (change condition).
- There must be a model of the system that describes what will happen if changes are made to the system (model condition).

This model condition is particularly critical to this review, because it argues that "….to control a system, a control device, such as a decision maker, must have (or be) a model of the system it seeks to control" (Brehmer, 1990, p. 265). This requirement, of course, is the reason that understanding the mental models that people develop as they work to control dynamic systems has been seen as a critical task for control theory researchers.

From the perspective of control theory, there are two basic control strategies (Brehmer, 1990). These include feedforward control and feedback control. Feedforward control relies on predictions about the future state of the systems, and feedback control involves choices based on current system information. Moreover, these distinct strategies require somewhat different models, and have different requirements for optimizing control over the system.

In the case of feedforward strategies, then, they require that the system does not change over time. And, in building a model of the DDM situation, the decision maker is typically one of many actors in the situation. This person must not only "work ahead" and be proactive, but must also figure the time requirements of the relevant processes into the working model of the situation. Expecting and building in delays will help to ensure that one's model of the situation is as accurate as possible. Another way to manage inevitable delays, Brehmer (1990) argues, is to decentralize the decision-making process such that there is less need for coordination.

For feedback strategies, however, they only need to consider how previous control actions have affected the system; hence, they can be much simpler. If accurate feedback information can be received, the biggest potential challenge is the magnitude of the delays in relation to the time needed to "correct" the system. If these delays are large, the situation could easily spiral out of control without the time for corrective action to be introduced. Hence, feedback strategies alone are not typically adequate for optimal DDM. Some studies have shown feedback control to be less effective compared to feedforward control in DDM (Schultz, Dutta, & Johnson, 2000).

Interestingly, Brehmer (1990) also argues that feedback strategies are inherently more likely to be used than feedforward strategies. They require simpler models, and they may be successful (even though suboptimal) and any apparent success may stifle the search for more proactive (and perhaps more successful) strategies. In a sense, this description of the dynamic decision maker argues that people may be inclined to "satisfice" on a non-optimal solution because it requires a less demanding model of the situation. This use of simpler mental models, moreover, is also argued to be one of the reasons why researchers have had difficulty capturing mental models. Brehmer (1990, p. 267-268) argues

> "…we cannot always expect the decision maker to have a well-developed model of the task. If decision makers follow a feedback-control strategy, the need for such models will not be obvious to them. Although they will need some model of how different actions will affect the system, this is not the same as having a general model of the task. Therefore, if our subjects are unable to answer questions about the nature of the task system, this cannot be interpreted as evidence that they are unaware of their model; it may simply mean that

> we have probed for the wrong model, that is, that we have asked for information pertaining to feedforward control when the subjects are following a feedback strategy."

The key focus in control theory, then, involves understanding the strategies that people use, and their models of the relevant task. The key issues relate to how the decision maker uses feedback from the environment, and whether the model is more complex (in the case of a feedforward strategy) or simple (in the case of feedback strategies). In opposition to rational models of human decision-making, then, where the decision-maker is making discrete choices, control theory focuses on the "continuous flow of behaviour and monitoring one's progress toward some goal rather than discrete episodes involving choice dilemmas" (Brehmer, 1990, p. 268).

It is important to note, however, that Brehmer's use of control theory to understand DDM is intended to be used in a "loose metaphorical way" (Brehmer, 1991, p. 268) rather than formally, because "current forms of control theory are not really congruent with what we know about human behaviour". Control theory requires input to be described in terms of measured individual signals, whereas human perception is based on patterns and gestalts. Because of the importance of patterns and gestalts, then, mathematical equations may be of little use for modelling human decision-making (Brehmer, 1990). Acknowledging the restrictions associated with using control theory as a framework for DDM research, Brehmer (1992; 2000) argues that control theory be used as a metaphor for DDM.

Gibson, Fichman and Plaut (1997; as cited in Gonzalez, 2005) have built on Brehmer's (1992) application of control theory to understand DDM. Gibson et al. proposed a model of DDM learning based on control theory. Their learning model describes decision-making in terms of two submodels: the judgement submodel and the choice submodel. The judgment submodel states that people learn by minimizing the difference between predicted outcomes and actual outcomes, whereas the choice submodel states that people learn by minimizing the differences between choices predicted by the judgment submodel and the choices they actually made. The Gibson et al. learning model of DDM has been implemented computationally via neural networks and has been found to provide a good account of learning in dynamic situations as well as how knowledge is transferred in novel situations (Gibson, 2000; as cited in Gonzalez, 2005). Therefore, it can be seen that control theory is a useful way to help understand DDM even if it can not be used directly as a theoretical model of DDM.

3.3 Microworlds

According to Brehmer (1992), a key component of making correct decisions is having an accurate model of the decision situation. When the situation and the model of the situation differ, errors are inevitable. One way of developing more accurate measures of people's learning and decision-making is by developing more accurate decision-making models through the use of microworlds (Elg, 1996). A microworld is a complex computer simulation used in controlled experiments designed to study dynamic decision-making (Gonzalez, Vanyukov, & Martin, 2005). Microworlds have been used to research DDM since the 1970s in Australia, Germany, the US, Sweden and Canada (Brehmer, 2000; Jarmasz, 2006).

Microworlds as a research tool are a compromise between the experimental control of laboratory research and the realism of field research (Brehmer & Dörner, 1993). Although microworlds are relatively simple, they embody the essential characteristics of real-world DDM environments (e.g., complexity, opaqueness). Simulations can represent the structure and complexity of aggregate dynamic systems with great fidelity and permit controlled manipulations of the decision contexts in

the system (Sterman, 1989; as cited in Elg, 1996). Therefore, microworlds provide the experimental control needed to develop explanations of DDM (Gonzalez, Vanyukov et al., 2005).

Researchers using microworlds have typically used two different strategies: the individual differences strategy and the experimental strategy (Brehmer, 2000). In the individual differences strategy, all participants interact with the same microworld under the same conditions. Analyses are conducted to explain differences in participants' scores in terms of performance on psychometric tests (e.g., intelligence test) or in terms of their behaviour while performing the task. The aim of the individual differences method is to find a way to predict task performance and to gain a better understanding of the demands that microworlds place on decision makers. In the experimental strategy, properties of the microworld are varied and the variations are assessed using between- or within-subjects designs. This method provides information as to what people can and cannot do under differing circumstances.

Results from research using the individual differences strategies suggest that people can be trained to cope with complex dynamic tasks (Brehmer, 2000). Microworld research indicates that individuals who perform well on complex dynamic tasks behave in a systematic way, collect more information before making decisions, evaluate their decisions more carefully, test causal hypotheses about the system, and exhibit more self-reflection than those who do not do well. Schaub and Strohschneider (1989; as cited in Brehmer, 2000) found that corporate managers showed the same kinds of behaviours as college students, but with greater frequencies of the beneficial behaviours. However, the particular factors leading to improved performance are not known. Repeated exposure, instruction in systems thinking, and instruction in the behaviours needed to perform better in complex microworlds do not seem to lead to better performance, whereas systematic reflection and learning specific rules for handling complexity seem to help performance (Brehmer, 2000).

Microworlds have also been used to measure key aspects of DDM. As noted earlier, Fu and Gonzalez (2006) used the beer game microworld to understand how people learn to identify relevant or irrelevant information in DDM. Gonzalez (2005) also used microworlds to understand how feedback is managed in DDM. According to Gonzalez (2005), there are three types of support of DDM: outcome feedback, cognitive feedback, and feedforward loops. Dynamically complex environments involve time delays and decisions that influence each other (positively or negatively) over time. In her study, Gonzalez used a microworld to simulate a Water Purification Plant in order to compare forms of feedback. Participants were tasked to process the maximum amount of water through a purification plant by either plugging, or emptying water basins. This is a highly time sensitive task with a specific window of time for each basin to fill and be emptied. Successful control in this microworld environment depends on precise timing. Systemic delays and deadlines are incorporated that adds complexity to the system.

Gonzalez (2005) assigned 88 participants into 5 conditions: one control group one feedback group, and three feedforward groups. In the control condition, participants were provided with the *total* number of gallons remaining in the system after expiration of all deadlines. In the feedback condition, participants were provided with performance-outcome feedback which consisted of the number of gallons of water remaining in the system for each deadline on the screen. In the first feedforward condition (Self-Exemplar), participants had the opportunity to reply their previous trials. In the second feedforward condition (Feedback-Exemplar), participants were provided with detailed feedback and had the opportunity to reply their own previous trials. In the final feedforward condition (Expert-Exemplar), participants had the opportunity to reply the previous trails of a highly skilled participant rather than their own previous trials.

The results of this study suggest that outcome feedback alone is not an effective form of decision support. That is, more detailed and frequent outcome feedback did not help improve performance on DDM tasks. In fact, the only decision aid that was successful was being able to see the previous trials of a highly skilled participant or “expert”.

Microworlds have also been used to understand DDM in a military context. For example, Bakken and Gilljam (2003) used a microworld simulation to conduct research on Combat Dynamic Intuition (CDI). CDI refers to a military commander’s ability to think and act in complex and highly uncertain situations (Bakken, 1993; as cited in Bakken & Gilljam, 2003). In particular, Bakken and Gilljam were interested in using Minimalist Decision Training to test CDI. Minimalistic Decision Training (MDT) was designed to be a simple and pedagogically focused simulation-supported system for the use of training of General level commanders. MDT scenarios put a commander or command group in charge of his own logistics and operations resources, but simplifies the operating environment by compressing time and space.

To test a prototypical MDT microworld, Bakken and Gilljam (2003) had 84 participants from local military academies and a business school take part in a study that simulated a humanitarian situation in which vaccines had to be transported. Participants were required to match supplies with capacity, order ahead (while taking into account transportation lags and supply chains), cut-off in ordering (when capacity utilization approached maximum), and balance the two supply chains.

The complexity of the microworld was varied through different levels of command. Participants were in command of an operational supply chain, a supporting supply chain, or both in combination. In addition, participants either read a brief or detailed cover story. Finally, prior to starting the trials, participants either practiced on each of the single supply lines in turn before embarking on the combined task (Simplified Approach) or practice on the combined task from the start (Full-Scale Approach).

The researchers found that participants who read the simple cover story performed better (M=105.5) than participants who read the more elaborate cover story (M=94.5), although this difference was not significant (p = .15). The researchers also compared the top 25% of performers to the bottom 25% of performers and found the best performers completed significantly more practice trials. As a result of this microworld study, Bakken and Gilljam (2003) suggest that minimalist decision environments are required, but not sufficient, conditions for acquiring operational skills.

Although, microworlds have been used as training environments for DDM, little is known about the factors that lead to effective microworld-based training. One attempt to address this issue was conducted by Jarmasz (2006). Jarmasz (2006) was interested in understanding whether the accelerated time environments found in microworlds enhance or inhibit the learning and transfer of complex system dynamics. To study this, Jarmasz (2006) conducted a pilot study to examine whether or not participants were able to learn simple DDM in an accelerated microworld environment and then perform the same task in a similar, slower (or real time) environment. The two main hypotheses motivating the study were 1) that DDM tasks rely heavily on pattern recognition process (Gonzalez 2003; as cited in Jarmasz, 2006) and 2) to see if what is learned in an accelerated environment is transferable to slower (or more real-time) environments. Jarmasz’s (2006) study used a microworld peace support operation with two groups: the first group was trained in real-time and the second group was trained in faster-than-real-time. Results from this research showed that overall the DDM task was difficult, but that the accelerated training group performed equal to or better than the real-time training group. Further, it was found that the accelerated group learned decision-making strategies that the slower group did not.

Results from this study suggest compressed-time microworlds can support training and transfer of DDM skills to real-time. This research suggests that dynamic pattern recognition can transfer across timescales (Jarmasz, 2006). These results were confirmed in in a full-scale follow-on study which validates microworlds as a potential source of inexpensive, flexible, faster training for command decision-making (Jarmasz, 2007).

Overall, research using microworlds suggests that people can be trained to conduct DDM and that microworlds are an appropriate platform for such training. Microworlds have also been shown to be useful in understanding DDM in military contexts as training using full-scale exercises or mission experience can be time consuming, expensive and dangerous (Jarmasz, 2006). However, concerns have been raised about using microworlds to investigate DDM (Gonzalez, 2005). In particular, concerns have been raised about the high variability in microworld characteristics. That is, although microworlds are often complex and opaque, they vary considerably in terms of dynamics and dynamic complexity. Furthermore, researchers have less experimental control when using a microworld than they do in laboratory settings. Addressing these two concerns will improve the effectiveness of microworlds to measure DDM.

3.4 Summary of Dynamic Decision-Making

As a whole, then, dynamic decision-making is required in environments with high risk and complexity, and involves the performance of tasks requiring multiple steps, that are inherently time sensitive, interdependent, and which exert influence over the surrounding environment as well as being influenced by it. Decision makers are required to perform the core task at hand, while simultaneously having to make allowances for the secondary effects of their efforts. This is often challenging because DDM environments can involve coordination among multiple players, and the need to maintain awareness both of what these players are doing, and of the problem space as a whole.

Dynamic decision-making has been explored from different perspectives, including systems theory, psychology, and control theory from the engineering domain. These perspectives put varying amounts of focus on different aspects of DDM. From the systems theory perspective, for example, the DDM environment is a dynamic system that ebbs and flows, and which is governed by the varying forms of feedback received. The focus in this perspective is on creating analogies that attempt to simulate the processes that people use to manage complex systems. These analogies, moreover, represent one way to help people to form more accurate models of the system. From the psychological perspective, on the other hand, the emphasis is often less holistic, and focuses on the sets of choices that people make as they attempt to make complex decisions. Much of the emphasis in more recent years has been on the intuitive processes that people use to make complex decisions under pressure. Decision-making, learning, and planning are all key focal points of the psychological approach to understanding DDM. Control theory has been promoted as another theoretical framework that could be used to understand DDM. This theory seems to have most closely aligned with systems theory (e.g., both emphasize the importance of feedback), but seems to focus on systems that are more constrained and simplistic than typically the case within systems theory. Control theory’s primary emphasis is on the role of feedback while managing a complex system.

Much of the research exploring dynamic decision-making has used microworlds to explore different aspects of DDM. This research has often explored the problems that people have understanding system dynamics. For example, some researchers have argued that people tend to have a poor understanding of the building blocks of system dynamics, including stock and flows

and time delays (Cronin & Gonzalez, 2007). Research from the psychological perspective, on the other hand, often has difficulties with DDM in terms of decision-making inadequacies (e.g., overoptimism, overreliance on heuristics). What seems common to all of these approaches, however, is that each makes assumptions that whether forming models of complex systems or making intuitive decisions based on very little information, people tend to form some sort of mental model to undertake DDM. These models are posited to help simplify the environment, and to make DDM easier and more manageable. The exact nature of these models, however, is the topic of the next section on mental models.

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4. Mental Models

This chapter explores the concept of mental models. The first section explores general definitions of the concept, followed by discussion of the different types or approaches to understanding mental models noted in the literature, and comparison of these approaches. Subsequent sections discuss how mental models are formed and applied, and both strengths and limitations of the mental model concept.

4.1 Definitions of Mental Models

Mental models research is prolific and has been used in many fields of study. The notion of mental models has been used in domains as distinct as cognitive psychology, business systems dynamics research, and human computer interaction. Specific studies of cognition and learning, including sentence comprehension, research on deductive reasoning, and causal reasoning have provided more detailed information on mental models (Klein & Hoffman, 2008).

At a broad level, mental models can be described as personal mental representations of our world. In fact, Toffler (1970; as cited in Wilson & Rutherford, 1989) defined mental models as subjective representations of external reality that everyone carries within their head. In reviewing the mental model literature, Wilson and Rutherford (1989) found consensus from literature that operators are assumed to have, or to form, an internal picture of system processes. These representations form the basis of mental models. They went on to define such "pictures" or representations as being concrete or abstract, dynamic or static.

Mental models are generally recognized to serve three key functions: to describe, to predict, and to explain our world. For instance, Markman and Gentner (2001) defined mental models as representations "of some domain or situation that supports understanding, reasoning, and prediction" (p. 228). Klein and Hoffman (2008) argue that mental models help people to generate expectancies and to plan future courses of action. Somewhat more specifically, Kolkman, Kok, and van der Veen (2005) describe mental models as residing "in the mind of individual persons, and determin[ing] what data an actor perceives in the real world, and what knowledge the actor derives from it. The mental model acts as the filter through which the actor observes the problem situation" (p. 320). In this sense, mental models help us to structure our experience, as well as help to filter the information necessary to understand our environment.

Rouse and Morris (1986) describe mental models as "the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states." (p. 351). A pictorial representation of this definition can be found in Figure 1.

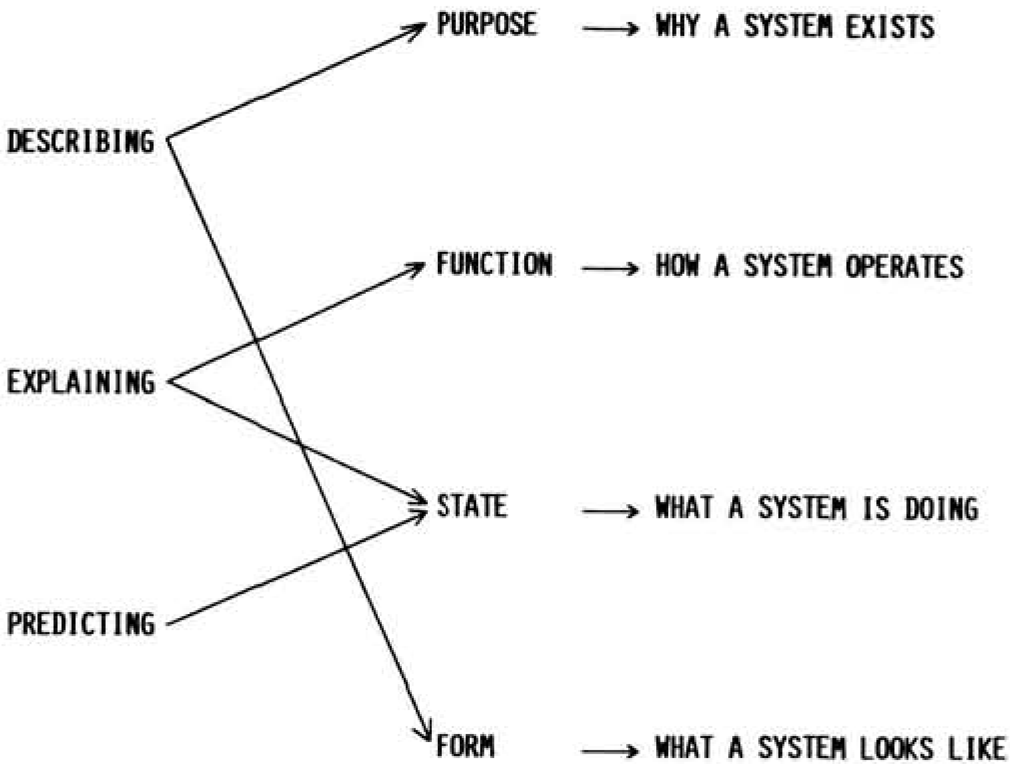

Figure 1: Purposes of mental models (Rouse & Morris, 1986)

As can be seen in the left column of Figure 1, the main purposes of mental models are to describe, explain, and predict a system. The ability to describe, explain and predict a system are directly related to understanding the purpose (i.e., why a system exists), function (i.e., how a system operates), state (i.e., what a system is doing) and form (i.e., what a system looks like) of the system. Specifically, the ability to describe a system allows us to understand the purpose of the system as well as the form of a system. The ability to explain the system allows us to understand the function of the system as well as the state of the system. Finally, the ability to make predictions about a system also allows us to understand the state of the system.

The current review aims to explore how mental models are understood across a range of relevant domains in which the concept is used. It should be noted here that our objective for this review is not to identify one clear and definitive definition of mental models, but rather to describe the existing definitions and discrepancies within the mental models literature. We will, therefore, spend the remainder of this section discussing several types of mental models, including propositional models, situation models, system dynamic models, and physical system models.

4.2 Approaches to Understanding Mental Models

Mental models research has been prolific in many areas of study. In this section we will discuss propositional models, mental models of physical systems, situation models, and mental models in system dynamics[1].

In developing a taxonomy of mental models, Moray (1996) categorized different approaches to mental models in terms of how these approaches treated the relationships between humans, the tasks they perform and their environments. Moray included figures similar to the one below (containing human, task and environment components), but with added interactivity arrows between the three parts. Where applicable, examples from this taxonomy are included in the sections below.

Figure 2: Components of Moray's (1996) taxonomy

4.2.1 Propositional Models

One of the biggest names in mental models research is Johnson-Laird. Johnson-Laird's approach to mental models focuses on the role of building mental models in order to perform deductive reasoning. Commonly called Propositional Models, these types of mental models have been studied extensively by others beyond as well. The primary focus of this approach emphasizes the role of mental models in syllogistic inferences. To some, this approach limits the extent of mental models, and is not accepted by all mental models researches as being the most applicable perspective (Staggers & Norcio, 1993). The process of understanding a syllogism requires "arguments from premises to an inference or conclusion" (Stylianides & Stylianides, 2007, p. 3). To do this, Johnson-Laird argues, people first construct a model of the information contained in the initial premises of the syllogism. He argues that reasoning depends on imagining the possibilities compatible with the premises, and drawing conclusions from these mental representations. The representations are created based on a series of propositions that include quantitative descriptors (e.g. all, none, some) of the general relationships (e.g. if, not, or, and) between a limited number of sets. For example, if faced with the premise of "Some of the chefs are musicians". None of the musicians is a painter" (Johnson-Laird, 2006, p. 219),, the first step would be to form an image of a

[1] This section will not include a discussion of mental models in control theory as no relevant literature in control theory was found relating to mental models. This is not surprising, as control theory is generally focused on an engineering perspective. That said, the importance of feedback in mental models (which is central to control theory) was found, and was included in the 'System Dynamics' section. Further, how users create mental models of physical systems was also found and is included in the 'Physical Systems' section.

group of people. This mental model has a structure that is similar to that of the situation it represents. At the next stage of reasoning, some of the chefs would be holding musical instruments, and others would be holding no musical instruments. Another set of people would be holding paintbrushes. Thus as more data is provided (or perceived) in a situation, that new piece of information is synthesized into the model, so that with each additional bit of information, the model is then adjusted. If more than one model is seen to be consistent with the premises, other models might be constructed. The decision maker then searches for evidence in support of the model, and makes some sort of conclusion. Then, the decision maker will search for "alternative mental models that may lead to refutation of the conclusion (counterexamples)" (Stylianides & Stylianides, 2007, p. 3).

The ability to form mental models, Stylianides and Stylianides (2007) argue, is dependent on several core abilities. Key amongst these is the ability to understand language, the ability to apply rules of logic, and the ability to search for alternative models. These skills develop as people mature, in conjunction with the increasing capacity to use working memory. In fact, they argue that errors in deductive reasoning often occur simply because people fail to consider all the possible counterexamples to the mental model that they create.

Through numerous reasoning studies Johnson-Laird (2001, 2005) has made a number of conclusions and predictions about mental models, as follows:

> *Mental models are iconic*. Accordingly, the mental model takes the same structure as the object the model is a representation of as far as possible, but certain components of them are necessarily symbolic. Johnson-Laird emphasizes that this iconicity is important.
>
> *One model* is better than many models in terms of improving reasoners' abilities. The fewer the number of mental models needed for an inference, and the simpler they are, the easier inference should be. It should take less time, and be less prone to error. Otherwise, if multiple models are required, reasoners sometimes fail to consider all models. This prediction is a consequence of the limitations of working memory (Johnson-Laird, 2001).
>
> *Mental models represent what is true, but not what is false.* Any manipulation that helps reasoners bring to mind the falsifying instance of the conditional improves performance in the selection task (Johnson-Laird, 2005). So reasoners can – with some difficulty – flesh the models out into fully explicit models. However, when falsity matters, fallacies do occur.
>
> *Formation.* Content and background knowledge modulate interpretations of the world so mental models are created to be consistent with the premises understood by the reasoner. This means that models are not necessarily based on unbiased truths, and instead do, at times, include inaccuracies.

Research led by Johnson-Laird demonstrates that the quality and availability of mental models has an important impact on human reasoning ability (Sparkes & Huf, 2003). Through proper use of mental models our reasoning ability is able to improve, and with experience reasoners are able to develop tailor-made strategies for particular sorts of problems.

Moray's (1996) representation for the abstract problem solving/propositional logic approach (typical of Johnson-Laird) is shown in Figure 3.

Figure 3. Mental models for understanding propositional logic (Moray, 1996)

As the task is typically an abstract reasoning problem provided to participants (e.g., patterns on cards, verbal descriptions), Moray (1996) reasoned that the only relevant link is from the task to the human. The information about the reasoning task becomes a mental model because the information is turned into a mental representation, which is manipulated by the participant to generate an answer (hence the feedback loop on the human dimension). Importantly, with this approach, then, the human is influenced by the task, but does not influence it. Interactions with the environment are also not prominent in this conceptualization of mental models.

There are a number of factors limiting the application of propositional models to dynamic decision-making. Mainly, this approach seems to focus on a very small subset of reasoning tasks that involve static finite constructs. Further, there is no interaction between effects of decision makers on the task or on the environment. Thus, these scenarios share little similarity to the complex, interdependent, and uncertain environments of dynamic decision-making. Still, there are a number of considerations about mental models that will be taken forward from this perspective. Namely, that humans have problems dealing with more than one mental model, that mental models do not tend to contain what is false and that mental models are formed based on the reasoners' perspective and are not always accurate.

4.2.2 Physical Systems

Mental models have also been used to describe, explain and predict the workings of physical systems. Forbus and Gentner (1997) define mental models as the models people use in reasoning about the physical world. Mental models are important in reasoning about complete physical systems, in making and articulating predictions about the world, and in discovering causal explanations for what happens around us. In her discussion of mental models, Gentner (2002; Markham & Gentner, 2001) distinguishes between the logical and the causal mental models approach. The logical models approach focuses on mental models as working memory constructs that support logical reasoning (e.g., Johnson-Laird). However, Gentner's focus is on the causal models approach. This approach seeks to characterize the knowledge and processes that support understanding and reasoning about physical systems and mechanisms. Markman and Gentner (2001) define causal mental models as "mental representations that are used in reasoning and that are based on long-term domain knowledge or theories" (p. 229). In particular, causal mental models are used to explain reasoning about physical systems and mechanisms (e.g., human-computer interaction, ecology).

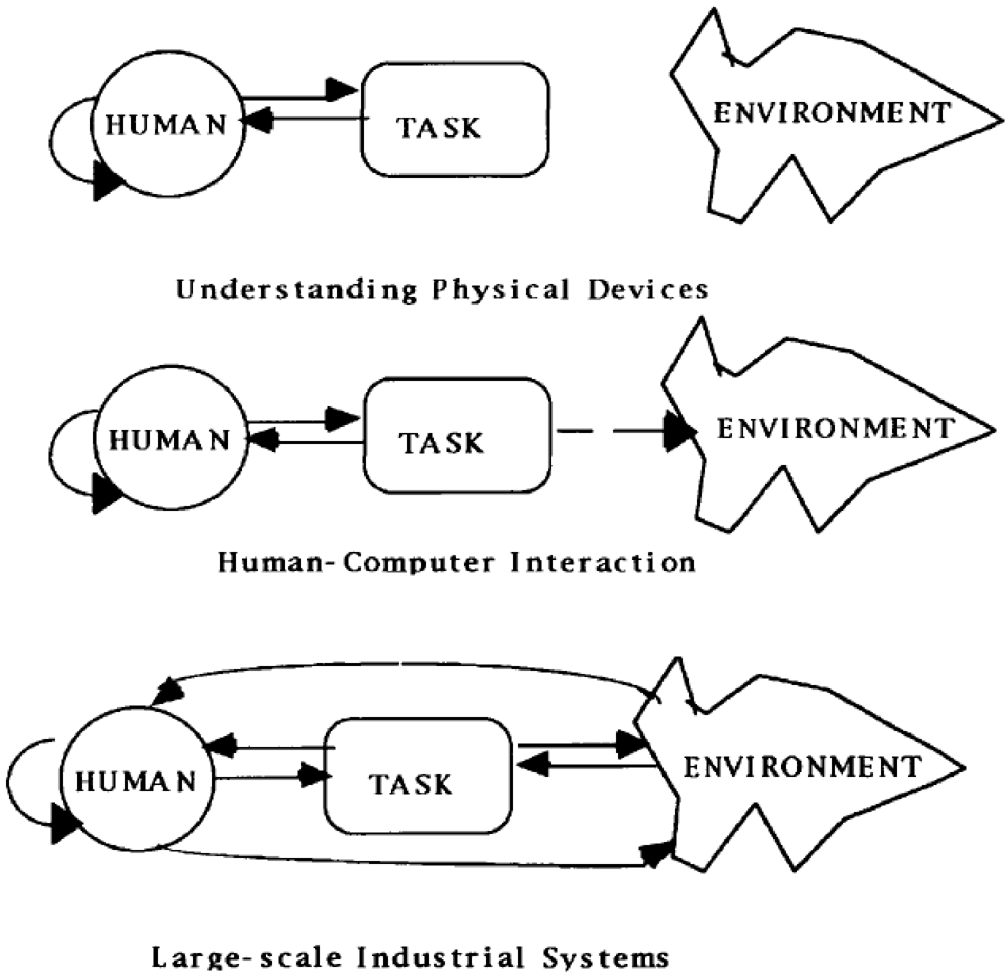

Figure 4. Mental models for understanding physical systems (Moray, 1996)

With respect to physical devices, Moray (1996) states that mental models are developed as information predominantly flows from the device to the person. The information received then becomes incorporated into the mental model. The contents of the mental model are examined and manipulated to construct a causal account of the functioning of the device. The environment does not figure prominently in this process. For human-computer interactions, the mental model is seen as a generator of action. Therefore, the emphasis is on action generation, represented by an arrow from the operator to the task. Within large-scale industrial systems, the systems themselves are too large for operators to be able to track exact values of all variables from moment to moment. As the sheer size of large industrial systems does not allow operators to be fully up to date on the state of the system, operators depend upon their mental models for sufficient understanding to control the system.

In addition to physical systems and mechanisms, mental models can be used to reason about physical events (Markham & Gentner, 2001). Such models incorporate a small number of variables about an event, which variables are often qualitative rather than quantitative. That is, people reason about relative properties of physical systems (e.g., direction of motion, relative speed, relative

mass) but do not estimate values in specific quantities or carry out mathematical simulations of a system's behaviour(Markman & Gentner, 2001). Over time, people typically possess multiple models of complex systems, some highly context-bound and others more abstract. This is consistent with work done by Rasmussen, Pejtersen, & Schmidt (1990) that looks at explaining the same system at variable levels of abstraction when designing interfaces for complex systems. Rasmussen (1979) states that "a system can be viewed as what it looks like, how it functions or why it exists. All of these views are 'correct' and of value for answering a variety of questions about a system" (as cited in Rouse & Morris, 1986, p 353).

According to the physical systems domain, operators form a representation of the physical system in their working memory (WM) by combining knowledge stored in their long-term memory (LTM) and using the information they acquire about task characteristics (Genter & Stevens, 1983; as cited in Cañas, Antolí, & Quesada, 2001). When dealing with physical systems, efforts are often focused on how information about the system representation is acquired and extracted from LTM (Cañas et al., 2001).

Mental models can serve a number of functions, such as enabling mental simulation and promoting learning processes. Simulations enable running a mental model internally, in order to observe how it will behave and what the outcome will be. Mental simulations often involve the use of imagery (Markham & Gentner, 2001). Furthermore, mental models can facilitate learning, particularly when the structure of the new learning is consistent with the model. For example, Kieras and Bovair (1984; as cited in Gentner, 2002) showed that participants could operate a simulated device more accurately and could diagnose malfunctions better when they had a causal mental model of its functioning rather than a mere procedural grasp of how the device operated.

According to Gentner (2002) people can hold two or more inconsistent mental models within the same domain. For example, a novice learner may give one explanation of why a towel dries in the sun and another explanation of what causes a puddle of water to evaporate without seeing any connection between the two situations (Collins & Gentner, 1987; as cited in Gentner, 2002). In fact, Gentner (2002) states that "novices often use locally coherent but globally inconsistent accounts, often quite closely tied to the details of the particular example. This pattern emphasizes the tendency of novices to learn conservatively, with knowledge cached in highly specific, context-bound categories" (p. 9685). However, people shift to using learned rules rather than mental models for reasoning as they gain experience with a domain (Markham & Gentner, 2001). For example, Schwartz & Black (1996; as cited in Markham & Gentner, 2001) asked participants to solve a number of gear problems. One such problem stated that there are 7 gears on a pegboard are arranged in a circle so that each gear meshes with the one next to it. If one gear was rotated clockwise, which way would the next gear move? When first asked the question, participants mentally simulated the motion of the gears, often with accompanying hand gestures. Over time, though, people learned the parity rule (that every gear in a sequence turns in the same direction, but adjacent gears turn in the opposite direction), and shifted from using their mental models to rules to solve the problems. Therefore, it appears that with experience people access their stored knowledge of the outcome to search for rules to help solve problems rather than carry out full mental simulations of the system's behaviour.

The literature on physical systems raises a number of issues pertaining to the ability of mental models to support DDM. For example, Gentner's (2002) definition of causal mental models (i.e., characterize the knowledge and processes that support understanding and reasoning in knowledge rich domains) suggest that such models would be useful in supporting DDM. However, there was little mention in the physical systems literature reviewed of how such mental models are created or

work in DDM environments. There is, however, an underlying assumption is that it is possible to have a coherent mental model of the physical system, i.e. that the system is not *too* complex for the mind. Whether this is accomplished through having one mental model or multiple models of the same system at different levels of abstraction would be important to know. In addition, the role of memory types (i.e. working memory versus long term memory) in creating and maintaining a mental model needs further discussion to understand how they would impact a decision maker's ability to conduct DDM.

4.2.3 Situation Models

4.2.3.1 Situation models as situation awareness

Situation models seem to be a more constrained form of mental models. The situation model is "the current instantiation of the mental model which is more general in nature" (Endsley, 2000a, p. 2). Endsley (1995) defines a situation model as "a schema depicting the current state of the mental model of the system" (p. 43). It is a dynamic representation of a person's knowledge and understanding of the *present state* of a system (Endsley, 2000a). A situation model may incorporate the value of different system parameters (e.g., level of fuel gauge), an understanding of the dynamics of the system (e.g., rate of change) developed from changes in the situation model over time, higher level comprehension (e.g., understanding the state of the system in a gestalt form in relation to human goals), and projections of future states. A situation model may also assign well understood situations to prototypical classifications of the system state.

In understanding this definition of a situation model, it is crucial to know that Endsley (2000a) uses the two terms "situation models" and "situation awareness" (SA) synonymously. She defines situation awareness as "a person's mental model of the world around them" or a situation model (p. 2).

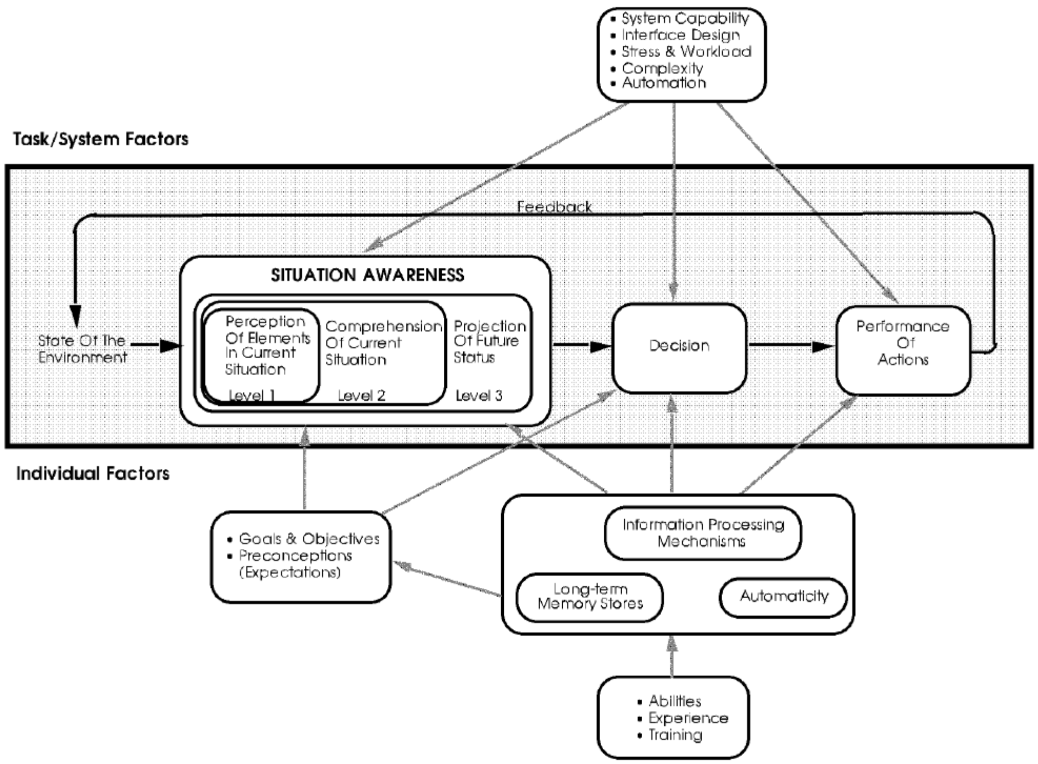

Figure 5: Situation Model in dynamic decision-making (Endsley, 2000b)

Figure 5 is a model of the overall decision-making process and provides the basis for understanding situation models within decision-making (Endsley, 1995). According to this model, people's perceptions of their environments form the basis of their situation model. Action selection (Decision) and performance (Performance of Actions) are separate stages that proceed directly from the situation model. Factors that influence the decision-making process include people's information processing mechanisms, preconceptions, goals and objectives.

Of importance to our discussion are the three levels that make up situation models (Endsley, 2000b).The first level is perception of cues. One needs basic perception of important information in order to form a correct picture of the situation. The second level is comprehension, which refers to one's ability to integrate multiple pieces of information and determine their relevance to one's goals. The final level is projection, which refers to the ability to project future events from current events and dynamics.

Time also plays an important role in the formation of a situation model (Endsley, 2000b). A critical part of the situation model is knowing how much time is left until some event occurs or until an action must be taken. "The rate at which information is changing is a part of SA regarding the current situation, which also allows for projection of future situations" (p. 4). As situations are dynamic, one's situation model must constantly change or be inaccurate.

Also of note in Figure 5 is Endsley's (2000b) vision of situation model as a state separate from decision-making and performance. The situation model is depicted as the operator's internal model of the state of the environment. Based on this representation, operators can decide what actions to

take to deal with the situation. Thus, Endsley envisions situation models as the main precursor to decision-making. She argues this is why it is possible to have a perfect situation model and still make an incorrect decision. For example, a battle commander can know where an enemy and what the enemy is capable of, but decide upon inadequate strategies or tactics to launch an attack.

Factors that impact the accuracy and completeness of situation models include attention and working memory (Endsley, 2000b). Where people direct their attention has a fundamental impact on the aspects of the environment incorporated into a situation model. Novice decision makers and those in novel situations must combine information, interpret the information, and strive to make projections within limited working memory.

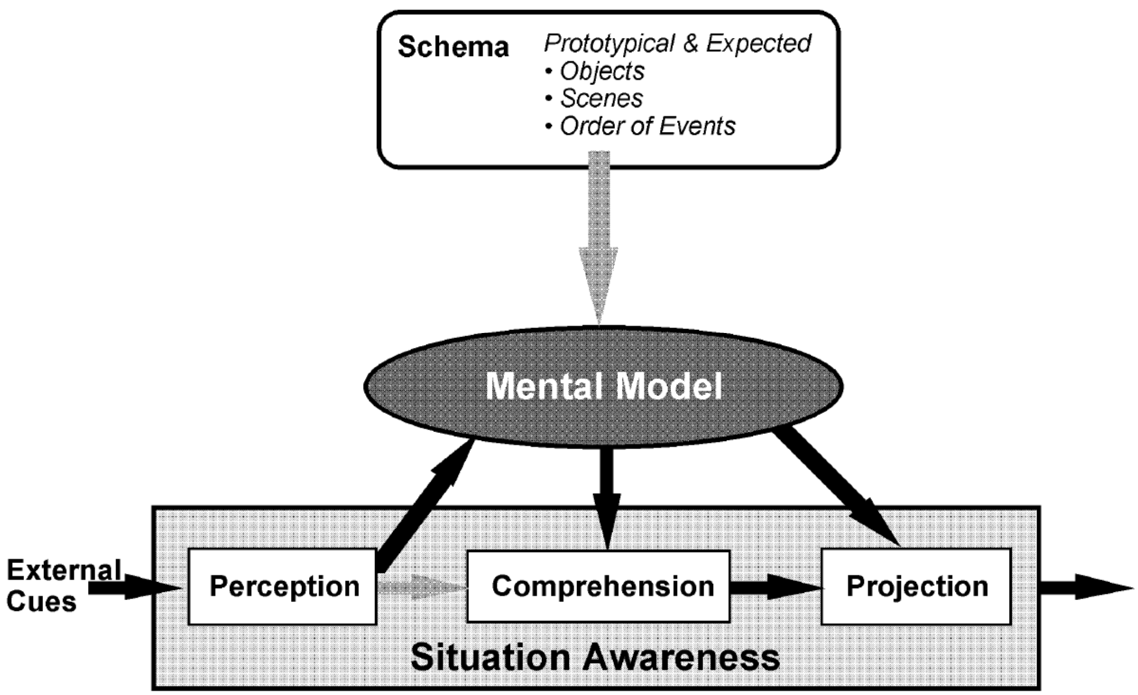

Figure 6. Relationship between the mental model and the situation model (Endsley, 2000a).

With respect to mental models, Endsley (2000a) states that mental models determine what information is attended to, how that information is interpreted and integrated, and any projections made about what will happen to the system in the future. Situation models, on the other hand, are developed by observing the world and using existing mental models. For example, a mechanic has a mental model of how an engine works, as well as a situation model of how the engine is functioning right now (carburetor problems), the state of its components (new or worn), and its capabilities and features (horsepower). Such knowledge is made possible by perceiving, interpreting, filtering and integrating information. Mogford (1997; as cited in Endsley, 2000b)

states that the mental model is the underlying knowledge base for a situation model. The information in a mental model influences and structures the situation model data and directs attention, which can be detrimental when the selection and interpretation of information from the mental model results in a faulty SM (Endsley, 2000b).

With respect to DDM, it appears that situation models are highly applicable. Situation models are run from a basic mental model of a system, but relate to what is going on at the moment. Therefore, they are always being updated. In addition, situation models are used to predict what will happen in the system in the future. Also, they have been studied in complex, uncertain contexts showing that they could likely be used in DDM environments.

4.2.3.2 Situation Models and Narratives

The basis of language comprehension is a reader's ability to construct mental models of the situation being described (Bower & Morrow, 1990). Comprehension of a text, thus, requires the construction of a mental representation of what the text is about: a situation model. With respect to narratives, situation models are "mental representations of the people, objects, locations, events and actions described in a text, not of the words, phrases, clauses, sentences and paragraphs of a text" (Zwaan, 1999, p. 15). The situation model is used to interpret and evaluate later statements in the text. It is the mental representation, rather than the text itself, that readers remember (Bower & Morrow, 1990). Much of what a dynamic decision maker learns about the world is through text (e.g. emails, articles, Powerpoint presentations, reports, etc). While DDM is not explicitly formed through narrative text, there are lessons here that are applicable.

According to Bower and Morrow (1990) a situation model of a narrative contains two major parts. First, there are the descriptions of the cast of characters, their occupations, relationships, and personal traits. These details explain the characters' goals, plans, and actions as the plot develops. Readers assume that goals and plans can explain a character's actions. These explanations allow readers to build a network of causal connections among events in the story. Because goals are the most important causes of characters' actions, readers set up a goal list of each character in their memory and monitor how story events relate to these goals.

Second, there is a mental map of the physical settings in which the actions occur, also known as a spatial model (Bower & Morrow, 1990). This spatial model is a mental map of the places, landmarks, and objects as they are laid out in the narrative and the locations of characters as they move about in this space. Bower and Morrow suggest that readers "construct in imagination a sort of theatre stage or 'doll house' with landmarks and rooms filled with expected objects, plus any special objects mentioned in the text" (p. 45).

When we are engaged in a narrative, we have a certain vantage point (spatial, temporal, and psychological) from which we experience the event vicariously. Zwaan (1999) refers to this perspective as a deictic center. The following aspects of a narrative are relevant to a deictic center (Zwaan & Radvansky, 1998; Zwaan, 1999):

> Space. Situation models should represent relevant aspects of the environment. Readers are faster to recognize words denoting objects closer to the protagonist than farther from the protagonist (Zwaan, 1999; Bower & Morrow, 1990). When readers have a spatial model of the narrative, they update their representations according to the location and goals of the protagonist and, subsequently, have the fastest mental access to the room the protagonist is currently in or is heading towards.

Time. We assume events are narrated in chronological order (Zwaan, 1999). This is because we experience events in our lives in chronological order. Therefore, people who construct situation models find it more difficult to comprehend text that is presented out of chronological order.

Goals and causation. Unfinished goals are more prominent in our minds than goals that have already been accomplished (Zwaan, 1999). This is the same when reading text. Goals that the protagonist has not yet accomplished are more accessible to the reader than goals that have already been accomplished. We also have a strong tendency to interpret events as being causal and, therefore, infer causality.

People and objects. Readers are quick to make inferences about protagonists (e.g., personality characteristics, emotions), presumably in order to construct a more complete situation model (Zwaan, 1999). Reading speed is faster when stereotypes are held (e.g., male electrician) than when they are violated (e.g., female electrician).

4.2.4 System Dynamics

The concept of mental models is vitally important to the field of system dynamics (Doyle & Ford, 1998). The information gleaned from mental models about the structure and relationships in dynamic systems allows for the construction of system dynamic computer models in the absence of written and numerical data. Consequently, system dynamics researchers have devoted much effort in developing techniques and procedures for eliciting, representing, and mapping mental models. Conversely, the goal of most educational interventions in system dynamics is to change or improve mental models in order to improve the quality of dynamic decisions.

Unfortunately, there is no coherent definition of mental models within the system dynamics field. In order to provide some specification and clarity to the mental models literature, Doyle and Ford (1998) proposed that system dynamics researchers are primarily interested in specialized cognitive structures they termed “mental models of dynamic systems” (MMODS). The term “mental models”, therefore, is an abbreviation of MMODS. MMODS is a “relatively enduring and accessible, but limited, internal conceptual representation of an external system whose structure maintains the perceived structure of that system” (p. 19).

At the heart of decision-making within system dynamics is feedback theory**.** The basis for decision-making within feedback theory is the cybernetic loop (Richardson, Andersen, Maxwell, & Stewart, 1994). This loop involves the state of the system, the perceived state, goals, planned action, and action affecting the state of the system, and closing the loop of perception, planning, and action. According to feedback theory as proposed by Richardson et al. (1994) “a mental model in a dynamic, planned action setting must be composed of (at least) these four elements: intentions, perceptions, system structures, and plans” (p. 182) as illustrated in Figure 7. This system dynamics approach, which Richardson et al. (1994) refer to as feedback theory, focuses on the elements of a mental model and the connections between those elements.

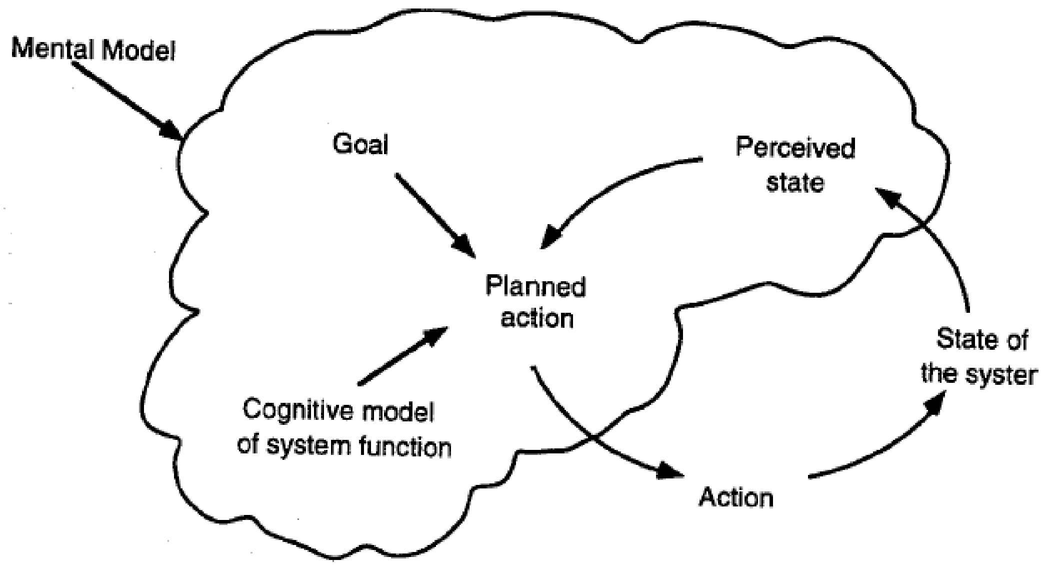

Figure 7. Components of mental models placed in the context of the classic cybernetic process (Richardson et al., 1994).

Within feedback theory, a mental model comprises three submodels: the ends model (goals), the means model (strategies, tactics), and the means/ends model (relation between goals and strategies or tactics) (Richardson et al., 1994). The influence of all elements of this view of a mental model (shown in Figure 7) are connected. However "…ignoring their distinguishable characteristics can be misleading" (Richardson et al., 1994, p. 183).

- Ends model focuses on the goals and contains perceptions and information about what one is trying to accomplish in a decision or a number of decisions over time. There are local or proximal goals (i.e., intermediary goals) and global or distal goals (i.e., major or ultimately important ends to strive for). A person's ends model in DDM tasks includes this set of local-to-global goals.
- Means model focuses on the strategies, tactics, and policy levers decision makers believe are available as they move towards their perceived goals.
- Means/ends model focuses on the connection between the ends model and the means model. This model can be a mental representation of the stock-and-flow/feedback structure of a complex dynamic system. It could also be a simple chain of associations linking a policy lever to an outcome.

However, Richardson et al. (1994) criticize the feedback theory vision of mental models as an inadequate foundation for mental model research on DDM. They state that the theory's treatment of perception is woefully weak and it fails to incorporate structures for learning. Subsequently, Richardson et al. proposed their own vision of mental models.

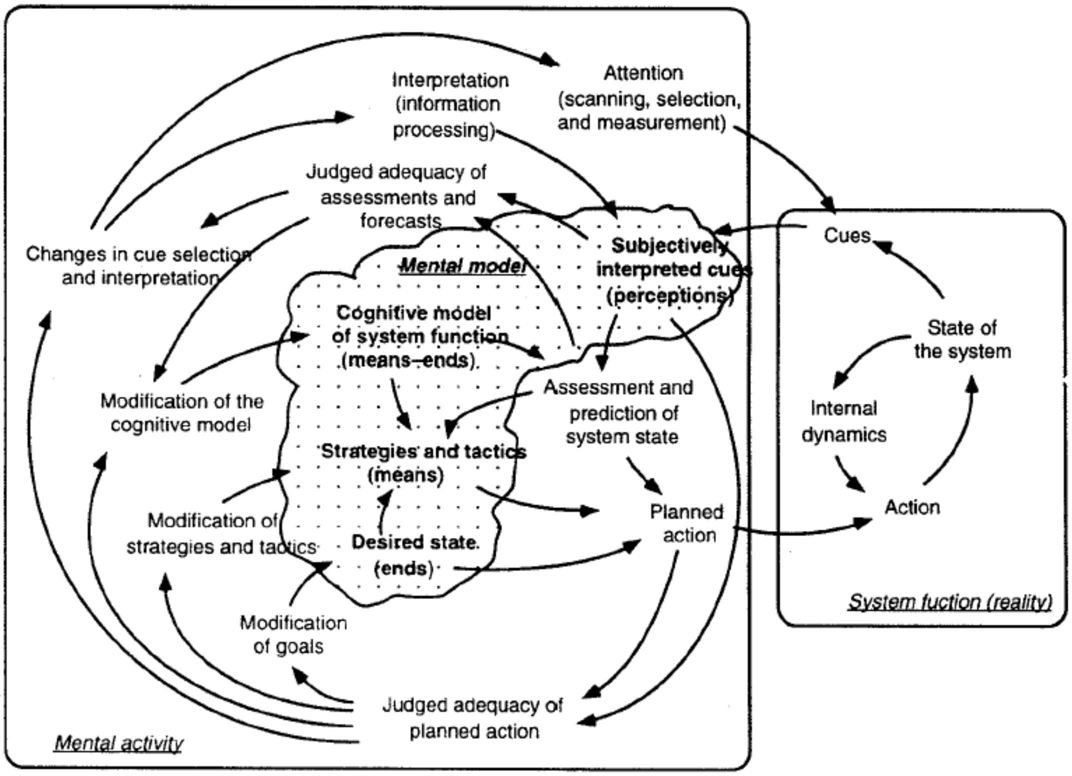

Figure 8. Integrated theory of perception, planning, action, and learning (Richardson et al., 1994)

In composing their model, Richardson et al. (1994) incorporated ideas from the Brunswickean lens model into the feedback theory model to develop their representation of mental models. Within the Brunswickean lens model, the "perceived state" is a complex process involving true descriptors of the state of the system, cues and measurements derived from the descriptors, and subjective cues (Richardson et al. 1994). Subjective cues are a combination of objective cues unconsciously assembled by the observer. They are the result of scanning a field for all possible cues, selecting combinations of cues to attend to, and gauging the cues. These cues are then subjectively interpreted in light of experience, memory, and perceptions. Assessments of the current system state and predictions for future states are made from these subjective cues.

Within the Richardson et al. (1994) model, an observer scans the system, selects and interprets cues from it, and subjectively interprets them as a basis for assessing and predicting the state of the system. Assessments and predictions are based on the observer's cognitive model of the system. Comparisons of the desired state and the current state result in the selection of strategies, tactics, and policy levers. Richardson et al. also included mechanisms for learning, as they felt omitting this mechanism was a weakness of previous models. They state that learning is the mix of processes that allow people to change their mental models.

According to Richardson et al. (1994), their model incorporates observers' ability to modify their thinking to improve assessments, predictions, and/or interventions in complex dynamic systems by 1) changing the cues they pay attention to and how they are interpreted, 2) change the way they

think about how the system functions, 3) change the strategies and tactics they are using, and 4) change the goals they strive toward.

Richardson et al.'s (1994) vision of mental models appears well suited for supporting dynamic decision-making. The means/ends model includes a feedback system so that the decision maker is able to make adjustments to his or her mental model. This accounts for learning, the "…process by which people change their mental models" (Richardson et al., 1994, p.186) that assist in creating a more accurate mental model of the system.

4.2.5 Overview of Prominent Approaches

The various approaches to understanding mental models emphasize different aspects about them. In an attempt to clarify these different aspects Table 3 below was created. There was a great deal of discussion about these mappings, and some disagreement (which are reflected by '?') due to different interpretations within and across the approaches.

Table 3: Similarities Between Approaches

	Johnson Laird	Situation Models	System Dynamics	Physical Systems
Cognitive representations	√	√	√	√
Alternative models are generated	√	√	—	√
Series of propositions	√	—	?	—
One best model	√	—	—	—
Real-time representation	—	√	—	—
Content and background knowledge modulate interpretations	√	√	√	—
Visual representation	√	√	?	√
Dynamic	—	√	√	√
Perception of cues	—	√	—	—
Includes understanding of current state	√	√	√	√
Projection of future events	—	√	√	—
Time critical	—	√	√	—
Representation includes the environment/context	—	√	√	√
Goal oriented	—	?	√	√
Used to explain physical systems and/or events	—	—	√	√

There are very few similarities between all of the mental models discussed above. The only similarities that hold true are that mental models are that they are cognitive representations and that they include understanding of the current state. The most similar perspectives appear to be System

Dynamics and Physical Systems, with Johnson-Laird's propositional models appearing to be the most distinct.

4.2.6 Challenges to Understanding Mental Models

Our review suggests two primary challenges inherent in understanding the concept of mental models. These relate to the lack of a clear definition, and the related problem of capturing and measuring mental models. Both of these issues have been raised in previous reviews on mental models (Rouse and Morris, 1986; Staggers & Norcio, 1993), though neither appear any closer to being solved.

4.2.6.1 Lack of a clear definition

Even though the notion of mental models is widely accepted in many research fields, there is no set definition of mental models. The lack of a consistent and coherent definition was indicated in early research (e.g., Rouse & Morris, 1986), and is noted even in more recent research. Cañas, Antolí, and Quesada (2001) state that "…a theoretical problem exists, which is reflected in the great confusion concerning the definition of a mental model". Wilson and Rutherford (1989) argue that some definitions of mental models describe hypothetical constructs that assist scientists in understanding behaviour, whereas others are entirely domain-oriented. Some authors attempt to define mental models through comparison with other structures "Mental models are best introduced by contrast with the notion of a schema…" (Holland, Holyoak, Nisbett, & Thagard, 1986, p 12). Based on their literature review, Kolkman, Kok, and van der Veen (2005) have argued that the term "mental model" is used in many disciplines, each having its own specific definition. Within distinct research fields, there is a lack of consensus about what mental models actually are.

In the field of system dynamics, there has yet to be developed an unambiguous and agreed upon definition of mental models (Doyle & Ford, 1998). In their review of mental models research, Doyle and Ford (1998) found the definitions of mental models to be overly brief, general, and vague. Furthermore, Doyle and Ford found that authors within system dynamics and cognitive sciences disagreed on what they considered to be the basic characteristics of mental models. In addition to a lack of a strong definition, there is also a lack of consensus as to what term to use to define mental models. For instance, within the human-computer interaction literature, mental models are also referred to as conceptual models, cognitive models, component models, and causal models (Staggers & Norcio, 1993).

The lack of consensus has had several consequences (Doyle & Ford, 1998). First, researchers have developed and applied idiosyncratic conceptions of mental models, which has hindered communication within their own field (i.e., system dynamics). In addition, the various definitions within the field have meant that different research techniques are used. One of the impacts of this is that research results cannot be cumulated across research programs. Finally, the lack of consensus across fields ultimately limits the ability of researchers within each field to share their techniques, insights, and research results with researchers from other fields

Staggers and Norcio (1993) looked at the role of mental models in human computer interactions. Though some argue that the term "mental models" has become meaningless, Staggers and Norcio argue that they have in fact become too meaningful. Without precise definitions, the terms are meaningful on intuitive appeal, because they mean whatever readers want them to mean. The only basic requirement is that readers adopt the premise of the mind operating in a symbolic fashion.

This raises the question of whether researchers using different approaches are actually using the same underlying construct when they talk about mental models.

Beyond using the same term ("mental models"), the relationship between the smaller scale mental models that are the focus of Johnson-Laird's reasoning research and the larger picture mental models that play a role in Endsley's situational awareness is not clear to the authors. At issue is whether or not the different mental models are in fact the same cognitive construct, or at least based on similar cognitive constructs. This has simply not been explored in the literature. Characteristics from each of the approaches should be empirically compared to determine whether the two (or more) theories can co-exist, which would support the idea that the different types of mental models are cognitively similar (or not). The current report will assume that there is overlap between the theories, focusing on common traits across approaches.

4.2.6.2 Measuring mental models

Endlsey (2000a) stated that the utility of mental models "has been limited by an inability to reliably extract and represent mental models in applied situations. The field of cognitive psychology may be a long time in answering the basic scientific question: do people really store knowledge this way?" (Endsley, 2000a, p. 5). One reason why it is difficult to measure mental models is because an observer's knowledge of a mental model is deeply embedded within the observer, making the model difficult to verbalize (Endsley, 2000a). Regardless of this difficulty, researchers have used a number of methods to try and measure mental models, including:

- Inferring characteristics via empirical study. For example, the traditional psychological approach to mental models research is to use experimental methods to infer the characteristics of models. Such methods provide only indirect insights into the form and structure of mental models; however, once externalized, changes in these externalizations are interpreted as changes in the underlying conceptual systems (Rouse & Morris, 1986). The creation of concept maps meant to represent externalized mental models is a common format (Johnson et al, 2006).
- Empirical modelling. Empirical modelling involves algorithmically identifying the relation between a person's observations and subsequent actions (Rouse & Morris, 1986).
- Analytical modelling. Analytical modelling involves the use of available theory and data to formulate assumptions about the form, structure, and parameters of mental models for particular tasks (Rouse & Morris, 1986).
- Verbal/written reports. When using verbal or written reports, researchers simply ask participants about their mental models (Rouse & Morris, 1986).
- Cognitive task analysis. Structured interviews, observation, and experiment-like methods to elicit data that are analyzed and represented as a description of how people think about various activities (Klein & Hoffman, 2008).

Regardless of the method used, Rouse and Morris (1986) note that "…the possibility of totally 'capturing' the mental model is rather remote. This is partly due to the high probability that a mental model is not a static entity having only a single form" (p. 353).

Rouse and Morris (1986) further note that it is difficult to measure mental models because researchers' conceptualization of a mental model is influenced by the domain being investigated as well as their background (e.g., psychology vs. engineering). Furthermore, mental models are

continually changing and efforts to elicit, measure, or describe them can themselves induce changes in mental models (Klein & Hoffman, 2008).

To deal with such issues, Rouse and Morris (1986) conceptualized differences in mental models in terms of distinctions among domains along two dimensions: the nature of model manipulation and the level of behavioural discretion (see Figure 9).

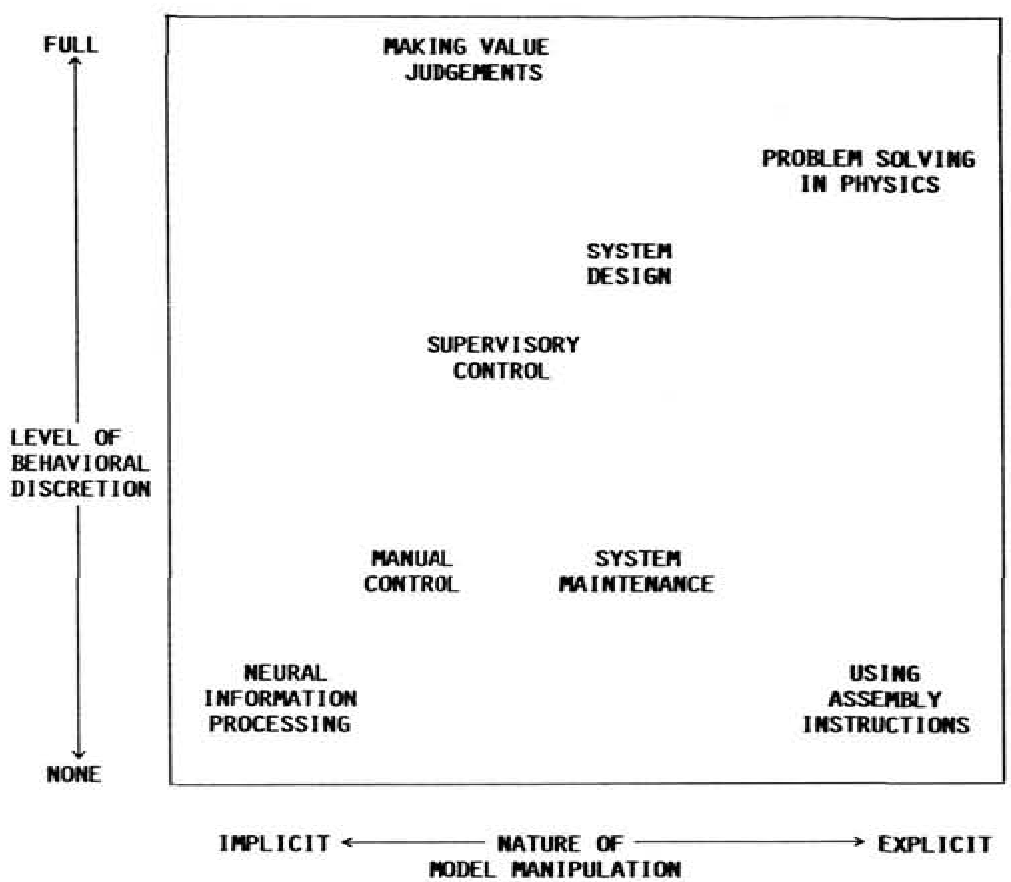

Figure 9: Distinctions among domains (Rouse & Morris, 1986)

Along the horizontal axis is the nature of model manipulation. This can range from implicit (i.e., the person is not aware of manipulating her mental model) to explicit (i.e., the person is aware that she is manipulating her mental model). On the vertical axis, behavioural discretion relates to whether a person's behaviour is a matter of choice or is dictated by the task. For instance, neural information processing is unlikely to be discretionary whereas tasks related to decision-making and problem solving are likely to be more discretionary. Behavioural discretion, then, can range from none to full.

Distinctions in Figure 9 provide a basis for explaining methodological differences among domains (Rouse & Morris, 1986). First, inferential methods (e.g., empirical modelling, analytical modelling) tend to yield more accurate descriptions when there is little discretion (i.e. situations that fall into the bottom portion of the graph) because the conceptualization can be based on external environmental or organizational constraints. Second, verbalization methods (i.e., interviews,

surveys) provide more appropriate descriptions when there is explicit manipulation. This is because the need for explicit manipulation (i.e. right side of the graph) may result in verbalization being a natural part of the task. Domains toward the upper left-hand part of Figure 9 are likely to present methodological difficulties in the sense that mental models will be elusive.

With respect to dynamic decision-making tasks, DDM is likely closer to 'full' in terms of the level of behavioural discretion that is involved (vertical axis). As stated in the above explanation, tasks related to dynamic decision making are high on this spectrum. However, its placement on the nature of model manipulation (horizontal axis) is more problematic. To some degree DDM spans this dimension, as mental models appear to be relied upon both consciously as well as unconsciously. Thus, depending on the decision maker, the task and the environment DDM would sometimes be in the upper right of the table. In these circumstances, the nature of mental models in dynamic decision-making should be possible to measure through verbalization methods. Circumstances when mental model manipulation is more unconscious would put mental models in the upper left, thus limiting effective measurement techniques. These results are consistent with the literature finding mental models hard to capture. Further study related to the consciousness of mental model manipulation is needed.

Cañas, Antolí, and Quesada (2001) conducted research to better understand the methods used to measure mental models. They argued that the problem with using techniques such as knowledge elicitation to capture the knowledge contained in mental models is that the model is only a simulation of the process is being measured. People give their responses based on a simulation of the real task, and only the knowledge used in that particular instance is elicited. Therefore, such elicitation techniques do not gather a complete account of all information within Long Term Memory (LTM), but access only the knowledge in Working Memory (WM). They argue that:

> "if a mental model is a knowledge structure that is simulated in WM, we must speak of the Mental Model as a process and as the result of that process. When we measure the Mental Model we are measuring the result of the simulation process. This result we take as a reflection of the knowledge structure that is stored in LTM... However, the simulation is accomplished by selecting the part of the permanent knowledge that is relevant for the task. That is to say, not all the knowledge is selected. The part that is selected will depend on the task, the context, the intentions, etc. It is also possible that the mental model, as measured, might be affected not only by selection but also by transformations performed on the knowledge in order to comply with the elicitation task" (p. 27).

To better understand this issue, Cañas et al. (2001) conducted a series of experiments to demonstrate that task characteristics affect simulations in WM and, consequently, what is inferred about knowledge of the system. Their hypothesis was that a "…mental model is a dynamic representation created in working memory by combining information stored in long-term memory and characteristics extracted from the environment" (p. 28). Results from their research suggest that variables introduced to impact WM had an impact on participants' execution of the elicitation task. All participants learned to interact with the system and could answer questions about the system, but their ratings about relationships within the system were impacted by what happened during the elicitation tasks. Subsequently, Cañas et al. (2001) concluded that elicitation tasks do, in fact, measure the content of WM, not the knowledge stored in LTM.

Thus it appears that trying to measure mental models is a complicated task. Our review suggests that although there are a number of approaches to capturing mental models, their use is somewhat dependent on the field of study of the researchers, and the assumptions that they make about what mental models actually are. Although there are concerns that such methodologies do not capture

mental models accurately, research by Cañas et al. (2001) suggests that some aspects of mental models can be captured by researchers. Furthermore, Klein and Hoffman (2008) argue that studying mental models can be manageable if we focus our inquiry on the knowledge that people have about specific relationships (e.g., cognitive task analysis).

4.3 Using Mental Models

It is also critical to consider research and theory related to how mental models are actually used. This sections explores the available literature relevant to how mental models are formed and updated, provides specific examples of mental model applications, and considers the benefits and challenges of using mental models.

4.3.1 Forming and Updating Mental Models

Although there is a vast literature on mental models, very little literature exists that provides a description of the cognitive processes involved when mental models are formed. Research that does exist suggests that mental models are built from the knowledge required to pursue a goal and the data perceived from the environment (Besnard, Greathead, & Baxter, 2004). That is, mental models are formed after an observer scans the environment of interest, selects cues from this environment, and subjectively interprets the cues (Richardson et al., 1994). A similar description argues that the information perceived and how it is interpreted is guided by pre-existing concepts (Bryant, 2004). Such pre-existing concepts, or mental representations, guide perception and information gathering activities. These concepts essentially tell us how to observe the world, discern what is and is not relevant, and relate observed phenomena to our goals (Bryant, 2004).

Denzau and Roy (2005) argue that mental models are contextual, and are learned in relationship to what we know, believe, and fear. We then assimilate knowledge into our mental models based on these beliefs. For example, Denzau and Roy (2005) stress the importance of one’s cultural background in shaping one’s mental models:

> Under conditions of uncertainty, individuals’ interpretations of their environment will reflect the learning that they have undergone. Individuals with common cultural backgrounds and experiences will share reasonable convergent mental models, ideologies and institutions and individuals with different learning experiences (both cultural and environmental) will have different theories (models, ideologies) to interpret that environment. Moreover, the information feedback from their choices is not sufficient to lead to convergence of competing interpretations of reality. In such cases multiple equilibria will result (p. 2).

It is also important to note that, when selecting cues from the environment, human decision makers need to be economical in their use of data (Bryant, 2004). It is not the amount of data that is the paramount factor, but rather the informativeness of the data. The informativeness allows the decision maker to evaluate the validity of his/her mental models (Bryant, 2004). This is consistent with Gonzalez (2005) who found that the absence of irrelevant information helps participants in DDM tasks (see section 3.2.1 for more on this).

Denzau and Roy (2005) state that the best conditions to form mental models are those in which an observer is observing a relatively simple situation, there is good quality information, there is frequent feedback, and the observer is sufficiently motivated to incur the costs of learning. It is

under these circumstances that an observer is most likely to learn the correct mental model through which to see the world.

When discussing the formation of mental models, a distinction must be made between forming a new model and forming the parameters of an existing model (Denzau & Roy, 2005). Research has shown that observers find it easier to incorporate new information into existing models than to form new models (Staggers & Norcio, 1993). This could be because forming new models depends on a number of factors; such as (a) the motivation of the user (b) the complexity of the system and (c) the complexity of the task. Whereas observers might be motivated to form a new model because of the perceived need for information in the system, the complexity of a task or system might inhibit the formation of new mental models.

According to Bower and Morrow (1990), the power of narrative can promote the formation of mental models. In a paper describing the role of mental models in narrative comprehension, Bower and Morrow (1990) argue that the basis of language comprehension is a reader's ability to construct mental models of the situation being described. Understanding a narrative involves:

> 1) translating text to underlying conceptual propositions, and
>
> 2) using world knowledge to identify referents of the text's concepts, linking expressions referring to the same entity, drawing inferences, and knitting together causal relations between action sequences.

As noted in section 4.2.3.2, comprehension of a text requires the construction of a mental representation of what the text is about: a situation model. The situation model is used to interpret and evaluate later statements in the text. Much of what a dynamic decision maker learns about the world is through text (e.g. emails, articles, powerpoint presentations, reports, etc). While DDM is not explicitly formed through narrative text, there are lessons here that are applicable.

A key intuition often associated with mental models is that they are 'runnable', i.e. there is a sense of deriving answers via mental simulation rather than logical reasoning. Many studies have looked at the idea that people learn how to make mental simulations of phenomena either in a series of dynamic images in the minds' eye or in more abstract mental models (Johnson-Laird, 2005). Thus, running the model is the process of manipulating the mental model in one's own head to test hypotheses about the reality the model represents. By using rules and structural relationships among objects, the model is run in a qualitative sense as well as in a more cause-and-effect mode (Staggers & Norcio, 1993). While this is cited as a common function of mental models, some argue that people's abilities to "run" their models are severely limited (Norman, 1983; as cited in Staggers & Norcio, 1993). Possible causes for errors include limited cognitive resources, erroneous mental models and mental models that are not complete enough to run. It is plausible that a concise and coherent mental model can be used to make accurate predictions about the real world, assuming there are only a limited number of variables to track.

4.3.2 Application of Mental Models

A number of examples found in literature seem to provide important information relevant to how mental models are used by people in settings such as military decision making, as well as.general problem solving and decision-making.

The Observe-Orient-Decide-Act (OODA) Loop has been a popular descriptive model of reasoning and decision-making within military circles for roughly 50 years (Bryant, 2004). Within this model, friendly and enemy forces are seen as being in competing cycles of decision processes. This

has allowed military theorists to identify ways to speed up enemy decision-making while interfering with and slowing down enemy decision-making. The key assumption is that completing one's own decision cycle faster than one's opponent will yield ever-increasing advantages in command and control (C2) effectiveness, which will, in turn, yield greater battle success (Alex, 2000; as cited in Bryant, 2004).

Bryant (2004) has criticized the OODA loop as an outdated model of cognition. Despite its intuitive appeal, he argues that the processes that people use to seek and use information and to generate and select courses of action are not explicit in this model. Moreover, it portrays command decision-making as reactive rather than proactive. It also overlooks the fact that decision-making has both "bottom-up" and "top down" components, and that critical thinking and constructive processes such as mental models help to guide human decision-making. He proposes an alternative descriptive model, the Critique, Explore, Compare, Adapt (CECA) Loop. This model is predicated on two mental representations. The first is the conceptual model, which is derived through the operational planning process. The second is the situation model, which captures the state of the battle space at a given moment in time. The conceptual model is "how you want it to be". It must be goal directed and describe the states of the battle space one wants to achieve across a specified period of time. This is much more important than describing what actions one believes should be performed to meet operational goals. The situation model is a representation of "how it currently is" (Bryant, 2004). The CECA model is shown in Figure 10.

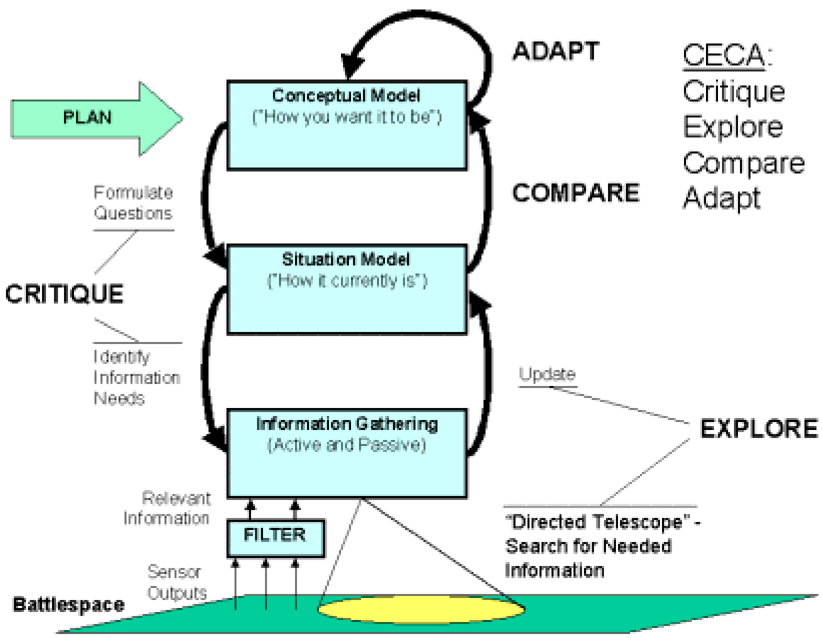

Figure 10: CECA Loop (Bryant, 2004)

The key to effective information management depends on minimizing attention devoted to information that does not have the potential to invalidate the conceptual model. Disconfirmatory evidence, which can indicate ways in which the conceptual model is not an accurate representation of the situation, is more valuable than confirmatory evidence (Bryant, 2004). Acknowledging this disconfirmation evidence can be a severe challenge for decision makers however (see Confirmation Bias the next section).

The Critique phase involves questioning the conceptual model ("how you want it to be") to identify critical aspects that if invalidated would render the plan for the operation untenable in some respect. The Explore phase comprises the active and passive collection of data from the battle space. The Compare phase involved comparing the "how it currently is" with "how you want it to be" and identifying any elements that are inconsistent with the current situation. The Adapt phase involves the decision maker determining what to do in response to the inconsistencies. All actions are driven by the conceptual model, which lays out the rationale for each action the own force might take (Bryant, 2004), consistent with Richardson et al.'s (1994) means/end models (discussed in section 4.2.4). The CECA model is a good example of how the concept of mental models has been used to elucidate complex decision-making processes.

Other research has also explored the use of mental models in military contexts, in relation to the decision-making skills of novice and experienced sea-combat trainees. After observing sea-combat trainees in training simulator scenarios, Lipshitz and Ben Shaul (1994) noticed important differences in how expert and novice trainees performed. They observed that experts collected more information about the situation before making a decision, engaged in more efficient information searches, "read" the situation more accurately, made fewer bad decisions, and communicated more frequently and elaborately with friendly units. To make sense of these differences between the expert and novice trainees, Lipshitz and Ben Shaul were interested in understanding differences between the experts' and the novices' mental models. They conceptualized mental models is "specific situation representations" (p. 293) that drive decision-making. However, they also argued that "mental models […] are labile entities that are constructed and discarded as decision-makers move, in time and space, from one situation to another (p. 298). Therefore, Lipshitz and Ben Shaul inquired into differences in experts' and novices' schemata, which are "abstract cognitive structures that guide the construction of mental models" (p. 293), to understand why the two groups constructed different mental models in identical situations. As schemata guide the construction of mental models through information search and interpretation, it is important to have adequate schemata in order to have an accurate mental model. Lipshitz and Ben Shaul argue that experts are more likely to have superior schemata.

To understand why the two groups constructed different mental models, Lipshitz and Ben Shaul (1997) turned to Klein's (1993; as cited in Lipshitz and Ben Shaul, 1997) Recognition-Primed Decision-making (RPD) model. Although applicable to the training scenario, Lipshitz and Ben Shaul (1997) did not feel that the RPD model could account for their observation that experts conduct more extensive and efficient information searches before making decision than novices. Therefore, the researchers added schemata to the RPD model.

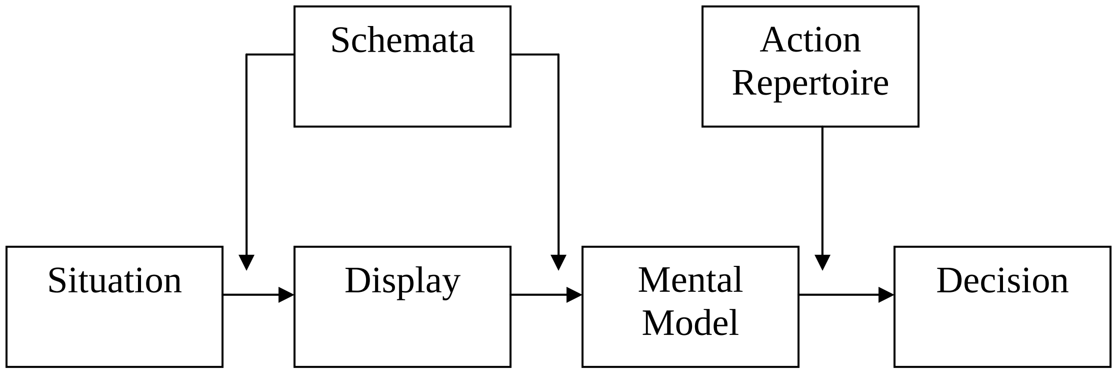

Figure 11. RPD model as schemata-driven mental modelling (Lipshitz & Ben Shaul, 1997)

Lipshitz and Ben Shaul (1997) argue that adding schemata to the RPD model explains the differences between expert and novice trainees that the RPD model could not explain otherwise. In turn, adding schemata to the RPD model, they argue, makes the RPD model more powerful.

Mental models have also been used to try to understand problem solving in general. For example, Kolkman, Kok, and van der Veen (2005) included mental models as a key factor in the problem solving cycle (see Figure 12).

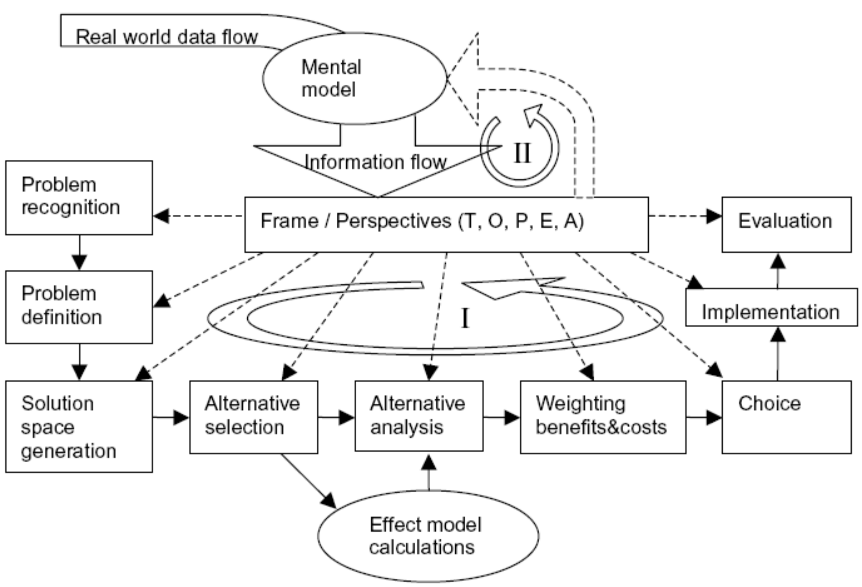

Figure 12. Steps of the problem solving cycle (Kolkman, Kok, & van der Veen, 2005).

Kolkman et al. (2005) state that the meaning of information is socially constructed and guided by different frames of perception. Such frames are one's underlying structures of belief, perception, and appreciation. The steps of the problem solving cycle are influenced by the frame of perception

and, indirectly, by the mental model. The mental model acts as a 'filter' that selects information from the 'real world' to be used in the frame. Mental models determine what data the observer perceives from the outside world and what knowledge the observer derives from it.

Mental models have also been used to shed light on dynamic decision-making within the health care industry. Shultz, Dutta, and Johnson (2000) were interested in understanding the thinking of health care executives as they engage in DDM tasks. In particular, they were interested in understanding relationships between mental models, use of feedback/feedforward decision control strategies, and changing conditions in the decision environment for health care executives.

Shultz et al. (2000) had senior healthcare managers assume the role of a Chief Executive Officer of an integrated health care organization and make resource allocation decisions over a simulated 20 year period of time. The researchers found that financial models and feedforward control (as opposed to feedback control) were characteristics of successful participants. They further found that health care executives tended to have mental models related to the financial viability of organizations rather than mental models related to quality of care. Finally, the more turbulent the changing environmental conditions were, the less successful participants were in completing the simulation.

Wilson and Rutherford (1989) note that mental models are of central importance within human factors research. They note that the concept of mental models is often used or invoked within human factors research in order to:

- Guide general design (e.g., "know the user's mental model");
- To summon the idea of a "picture in the mind";
- As experimenter-created or hypothesized models to measure task performance;
- Estimate the complexity of system use to enhance system design;
- To explain and describe behaviour;
- Used as a design tool.

Of course, the concept of mental models has continued to receive interest and attention because of the perceived benefits that they offer. Although mental models are argued to have a number of positive benefits, they are argued to be most useful in simple rather than complex environments, and in more familiar environments. Relatively simple environments/systems would require observers to perceive only a limited amount of information to form their mental models (Denzau and Roy, 2005). Simpler systems would also reduce the number of mental models that an individual is required to maintain (Johnson-Laird, 2001). Both these factors ease the mental workload in working memory required in using mental models, thus improving their efficacy. This characteristic is not consistent with dynamic decision-making environments where the systems are complex, full of interdependencies and uncertain.

As noted, mental models are also generally acknowledged to be most helpful in relation to familiar environments. Forming a mental model is not automatic. It takes effort on the part of an individual in order to select from the environment relevant data, integrate it with other information, and create some form of coherence. Once a mental model is formed, it is relatively simple to add information to that model (whether that new information improves the model or not) compared to the effort required to create a new mental model.

Our review showed strong support for the potential importance of mental models. In short, they help to simplify one's environment, and can assist problem solving and decision-making because they allow "short-cuts". Having a well-formed mental model can allow us to walk into a familiar

situation, and to know how to react, because our mental model can guide our behaviour. Mental models are parsimonious: often people do extra physical operations rather than the mental planning that would allow them to avoid those actions; they are willing to trade-off extra physical action for reduced mental complexity. This is especially true when the extra actions allow one simplified rule to apply to a variety of devices, thus minimizing the chances for confusions (Norman, 1983; as cited in Staggers & Norcio, 1993).

Just as mental models are argued to have adaptive value, however, they are also noted to have a range of shortcomings (e.g., Doyle and Ford, 1998). For example, mental models are not necessarily either accurate or complete. Some of the prominent shortcomings noted in the literature are as follows:

Limited cognitive capacity. Forrester (1994; as cited in Doyle & Ford, 1998) argued that people can only properly relate a limited number of variables. In fact, he states that even a skilled investigator is unable to anticipate the dynamic behaviour of a simple information-feedback system including more than five or six variables. This suggests that people are unable to create accurate mental models of highly complex systems.

Confirmation bias. Mental models have also been argued to be subject to confirmation biases. Besnard, Greathead, and Baxter (2004) state that the "weakness of mental models lies in their poor requirements in terms of validity: if the environmental stream of data is consistent with the operator's expectations, that is enough for the operator to continue regarding the mental model as valid" (p. 119). Overall, then, we are often motivated to see events as being in accordance with our beliefs and expectations rather than being inconsistent with them. This can lead to errors and biased reasoning processes, because we will tend to treat our experiences as evidence that our beliefs are correct and, erroneously believe that we have understood the problem at hand. Mental models can be conceptualized as a consistent set of expectations about a specific event or entity. As such, incoming information that is inconsistent with our mental models may well receive less weight and/or attention than it should. Therefore, such "co-occurring events can seriously disrupt situation awareness when humans are using mental models that are highly discrepant to reality but nonetheless trusted" (Besnard, Greathead, & Baxter, 2004, p. 118).

Incomplete information. Mental models have been described as being characterized by their incompleteness (Besnard, Greathead, & Baxter, 2004). This is because mental models have a limited scope and their content is only a partial representation of the environment, because of the limitations of human cognition (e.g., people forget the details of the system (Norman, 1983; as cited in Staggers & Norcio, 1993). Similarly, the number of elements that can be held in working memory is also limited. The resulting world view is one in which the essential features of a problem are overemphasized and peripheral data can be overlooked. Consistent with confirmation bias described in the previous paragraph, mental models can also be inaccurate because observers sometimes ignore new information and continue to interpret the situation in light of their formed but incorrect mental models. As noted by Moray (1987; cited in Staggers & Norcio, 1993), observers can have a tendency to become rigidly stuck in one mode and not update their mental model in the face of new information.

System errors. There are systemic errors in reasoning with mental models. People systematically overlook possible models of individual premises (e.g. they often incorrectly treat all x are y as referring to two co-extensive sets). Situations that call for a single mental model are reliably easier that those that call for more than one model (Johnson-Laird, 2005).

Erroneous. Mental models have been criticized as often being inaccurate or altogether erroneous (Klein & Hoffman, 2008). Research on laypersons' and students' mental models have found them to be "fuzzy, implicit, mostly wrong, vastly simplified, dynamically deficient, broad, amorphous" (Klein & Hoffman, 2008, p.61). Such erroneous findings have been found in research conducted to understand mental models on topics such as the causes of global warming, the workings of computers, and understanding risk. This is consistent with Johnson-Laird's (2005) findings that people make systemic errors in their models (e.g. they often incorrectly treat all x are y as referring to two co-extensive sets).

Overall, then, despite their potential contribution to human performance, mental models are also subject to a range of shortcomings that impact the accuracy of mental models are that people have a limited cognitive capacity, that humans often make erroneous causal links, that models are often based on incomplete information, and that systemic errors in reasoning impact mental models.

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5. Mental Models and Dynamic Decision-making

Having considered the concept of mental models from a range of perspectives, then, the goal of this section is to explore the usefulness of the mental model concept within the domain of dynamic decision-making. This section considers potential linkages between specific mental model approaches and DDM. The section that follows considers the requirements for optimally applying mental models while performing dynamic decisions.

5.1 Approaches to Mental Models and DDM

Previous chapters explored the nature of DDM and the various approaches to mental models prominent in the literature. The goal of this section is to understand the extent to which DDM could be supported by each of the unique approaches to understanding mental models. As alluded to already, there are a number of discrepancies between DDM environments and the context in which mental models are best applied. In general, the goal of the analysis was to be as inclusive as possible. That meant that instead of ruling out perspectives at first signs of a contradiction, we instead chose to review the entire perspective and try to tease out aspects that could be applicable in a DDM environment.

5.1.1 Propositional Models

While it is agreed that propositional models are based in psychology, it is difficult to see any substantive symmetries between the Johnson-Laird approach to mental models and the requirements of DDM. Instead, two specific aspects of propositional models will be discussed below. First, differences in the contexts of Johnson-Laird's studies versus DDM will be discussed. Second, the extent to which deductive reasoning is applied by decision makers in dynamic environments will be explored.

5.1.1.1 The Context of Propositional Models and DDM

In Johnson-Laird's studies, reasoners are presented with concrete, static relationship scenarios. While logically complex, they do not change over time, involve no interdependence between decision makers, and are relatively well structured. These situations are in high contradiction to the world in which dynamic decision-making takes place. While this does not mean that it is impossible for propositional models to play a part in DDM, it does limit their applicability. Casting human decision-making as requiring a high number of complex mental models seems at odds with the notion of proposition models. In fact, one of the conclusions from the reasoning studies was that reasoners perform better when there is only one mental model required where each mental model represents one set of possibilities. If applied to the DDM domain, this would mean that the decision maker creates a single model for each and every possible outcome. Given the sheer quantity of possible permutations, on even the simplest of dynamic decision-making tasks, it is highly improbable that decision makers are capable of doing this. Further, Johnson-Laird found that the differences between scenarios requiring two and three mental models were often so small that it was unlikely that reasoners constructed all three models.

If decision makers are challenged when they are required to create more than three mental models, perhaps this explains why decision makers in DDM scenarios sometimes do not fare well.

5.1.1.2 Deductive versus Inductive Reasoning

Proponents of propositional model theory depict decision makers as cognitively building on given parts of a construct to create a mental model. This mental model (or set of assumptions) is then used to deduce conclusions about the state of the world.

While the role of deductive versus inductive reasoning in DDM does not appear to be prominent in the available literature, some inferences about their potential usage can be made. There are some basic differences between deductive and inductive reasoning. Deductive reasoning involves deriving consequences from what is assumed. If the assumption is correct, then the consequence will be valid. Inductive reasoning is quite different. Inductive reasoning involves inferring a consequence based on multiple instantiations of similar scenarios where those scenarios have led to that consequence. Induction is not guaranteed to be correct, no matter if all the previous scenarios are in fact truthful (e.g. one may conclude that all swans are white as they have only ever seen white swans, but this does not mean that black swans do not exist). In general, errors in reasoning occur two ways (1) in deduction where the original assumptions are incorrect or (2) in induction where the consequence is in fact not generalizable.

Johnson-Laird's theories generally predict that errors are caused by the first error outlined above (i.e. errors in the mental model, which represent the assumptions and lead to incorrect consequences). While this is also logically applicable to DDM, the second error (i.e. induction errors) are also possible. This would occur when a DDM decision maker incorrectly believes that one scenario is like another scenario leading to incorrectly assumed consequences. Logically, these types of errors would occur even if the mental model (of previous scenarios) is correct. The relationship between inductive reasoning and mental models is further explored by Holland et al (1986) in their book *Induction.* They state that "despite their inherently transitory nature – indeed because of it – mental models are the major source of inductive change in long-term knowledge structures… [as] model construction provides the opportunity for new ideas to arise by recombination and as a consequence of disconfirmation of model-based predictions."

Research looking more into the role of inductive versus deductive reasoning and the role in DDM could prove interesting while also providing support for or against relations between propositional models and mental models.

5.1.2 Physical Systems

Mental models of physical systems are the models people use to conduct everyday reasoning about the physical world (Forbus & Gentner, 1997; Gentner, 2002). Such models are said to be important for reasoning about complete physical systems, making and articulating predictions about the world, and discovering causal explanations for what happens around us (Markham & Gentner, 2001).

Little of the literature discussing mental models of physical systems has been discussed in such a way that it can be related to DDM. In fact, there is a dearth of information to explain how such mental models are formed, how they are accessed, or even how they are used. Therefore, this discussion will focus on particular information items available about mental models of physical systems and how they might be related to DDM. We will also discuss key aspects of DDM and how such information is dealt with by physical system models.

5.1.2.1 Models of physical systems

Inconsistent models. Gentner (2002) states that people can hold two or more inconsistent mental models within the same domain. The example given was that of a novice learner who may give one explanation for why a towel dries in the sun and another explanation for what causes a puddle of water to evaporate without seeing any connection between the two situations (Collins & Gentner, 1987; as cited in Gentner, 2002). This begs the question: how do dynamic decision makers choose between inconsistent mental models when making dynamic decisions? It would be interesting to know what criteria are used to decide which mental model should be used in DDM tasks. We also wonder how having inconsistent models impact on the effectiveness of DDM.

Experience. Markham and Gentner (2001) suggest that people shift to using learning rules rather than mental models once they have gained experience with a domain. After repeated exposure to the domain, decision makers start to associate certain patterns with certain outcomes. Markham and Gentner (2001) argue that this leads experienced decision makers to access their stored knowledge of the outcomes rather than to carry out mental simulations. This assertion is based on the assumption that using mental models implies mental simulation (or 'running' of the mental models to predict outcomes with different variables). They assert instead that expert dynamic decision makers no longer use mental models at all, but rather rely on their heuristics and schemas to carry out DDM. This is important research for understanding the use of mental models in DDM, especially in comparing the effectiveness of expert and novice decision makers.

5.1.2.2 DDM variables

Control of the system. The main aim of the dynamic decision maker is to gain control of the environment (Clancy et al., 2003). However, there is no discussion of the observer using physical system models to control their environment. The literature simply states that mental models are used to reason about, make predictions of, and discover causal explanations for the every day environment (Gentner, 2002). This suggests that control is either not an issue when forming mental models for physical systems or that control is an issue that has not yet been explored by researchers.

Environment. Markman and Gentner (2001) state that developing mental models requires "long-term domain knowledge" (p. 299). Given the ever changing nature of DDM environments, the requirement for long-term domain knowledge may complicate dynamic decision makers' opportunities to gain sufficient knowledge to develop detailed and precise mental models of DDM environments. However, that is not to say that dynamic decision makes do not develop mental models of their environment at all. It could be that dynamic decision makers develop mental models in a manner similar to that of large-scale industrial plant operators. Moray (1996) states that operators of large-scale industrial plants cannot be fully up to date on the state of the system and must rely on mental models they have developed to control the system. We argue that there are similarities between the large-scale industrial plants and DDM environments. Both such "systems" are complex in nature, can have many variables for the decision makers to control, and do not allow decision makers the ability to be fully up-to-date on the state of the system. Given the similarities between large-scale industrial systems and DDM environments, it is possible that dynamic decision makers develop mental models of their environment in a similar fashion to that of operators controlling large-scale systems. Such mental models would then provide the dynamic decision maker with a sufficient understanding of the environment to be able to control the environment. It is worth noting that we did not find any literature linking large scale industrial system models and DDM.

Rate of Change. Over time, people typically possess multiple models of complex systems, some highly context-bound and others more abstract (Gentner, 2002). However, there is little indication in the literature about how quickly mental models are created. With the rate of environmental change for DDM tasks varying widely (Brehmer & Allard, 1991), it is unclear whether or not such mental models would be created fast enough to support DDM.

As can be inferred from the above discussion, there is not enough information at this time to fully understand the role that mental models of physical systems would play in supporting DDM. Information in the literature that could help understand such a role would include how feedback is incorporated into the models, whether or not the models are used in relation to goals, how the models are created, and whether or not they can be applied in dynamic environments.

5.1.3 Situation Models

In reviewing the literature, the situation models approach appears to be the one that could be conducive to supporting DDM. Endsley (2000a) describes situation models as dynamic representations of a person's knowledge and understanding of the *present state* of a system. Importantly, situation models are said to incorporate the dynamics of the system, the value of system parameters, any system changes over time, and projections of future system states (Endsley, 2000a). This means, in theory, that situation models should be able to support DDM, because these models allow the decision maker to incorporate changes to the system into their situation model to provide them with an accurate and up-to-date vision of system status and function. The decision maker can then use the situation model to make future system projections and, subsequently, decisions. However, the available literature did not provide details as to whether or not situation models are developed in the ways described by Endsley.

In order to evaluate the probability that situation models support DDM, we will first assess how well situation models support the various perspectives of DDM. We will then assess whether or not situation models are supported in DDM literature.

Situation models lend some support to the psychological perspectives of DDM. In particular, situation models are relevant for naturalistic decision-making (NDM). NDM considers decision in context-rich settings and the decision maker's situation awareness (Zsambok, 1997; as cited in Pliske & Klein, 2003). As noted earlier, Endsley (2000a) envisions situation models and situation awareness as being the same construct. Therefore, a decision maker's situation models would have an impact on the decisions made.

Situation models lend some support for the control theory perspective of DDM as well. In order to control a system, there are a number of conditions that must be met. These conditions include having a goal, the ability to control the system, the ability to change the state of the system, and the ability to have a model of the system that describes what will happen if changes are made to the system (i.e., to project what the system will look like if changes are made; Brehmer, 1990). The first 3 requirements are not addressed within the situation model literature. However, the literature suggests that situation models help to fulfil the fourth requirement. That is, the situation model is an up-to-date model of the system that can be used to make projections about the future of the system.

Although situation models seem to be the most consistent with DDM perspectives discussed in this report, the support is somewhat tenuous. The DDM perspectives do not provide the rich detail needed in order to make a stronger assessment of the usefulness of situation models in DDM. We, therefore, turn to the definitions of DDM to identify the utility of situation models in supporting

DDM. To do this, we first look to the three levels of situation models described by Endsley (2000b). These levels are:

1. The observer needs basic perception of important information in order to form a correct picture of the situation.
2. The observer needs to be able to comprehend the environment/system, specifically be able to integrate multiple pieces of information and determine their relevance to one's goals.
3. The observer must be able to project future events from current events and dynamics.

In order for situation models to support DDM, research should show that decision makers are able to attain these three levels of situation models.

The observer needs basic perception of important information. As has already been noted in this chapter, we have a number of cognitive biases restricting our ability to perceive important information. For instance, we tend to seek out information that supports our current belief of the system (Besnard, Greathead, & Baxter, 2004). In addition, Fu and Gonzalez (2006) also suggest that we do not perceive information accurately. As described in section 3.2.1, Fu and Gonzalez's research using the beer game found that participants tended to ignore temporal dynamics of a system and underutilize information that indirectly influenced the outcome of their decisions. These findings suggest that we are not particularly effective at perceiving important information from our environment.

The observer needs to be able to comprehend the environment/system. As with perception of information, there is reason to believe that decision makers have difficulty perceiving and comprehending their environment. This difficulty could be due to the fact that people have difficulty understanding temporal dynamics and feedback delays. After conducting research on time delays and feedback processes on DDM performance, Sterman and Diehl (1993) suggested that poor performance on DDM tasks was due to participants' inability to understand the system because of its complexity. Follow-up research conducted by Sterman (2002; as cited in Cronin & Gonzalez, 2007) suggests we have problems understanding system dynamics because we have a poor understanding of stocks, flows, and time delays. Not understanding these aspects of the system, resulted in participants developing insufficient mental models to adequately support DDM (Cronin & Gonzalez, 2007). Thus, it appears that dynamic decision makers are not particularly effective at understanding their environment either.

The observer must be able to project future events from current events and dynamics. Research was not found that speaks to decision makers' ability to project future events. However, it can be argued that if people are unable to meet the first two of Endsley's (2000b) requirements in DDM, it is doubtful that they would be able to project future events. That is, any projections made about future events would be based on limited information resulting in an erroneous mental model.

As outlined in section 4.2.3, Endsley views situation models as distinct from mental models. Specifically, mental models determine what information is attended to, how that information is interpreted and integrated, and any projections made about what will happen to the system in the future. Situation models, on the other hand, are developed by observing the world and using existing mental models. The information in a mental model influences and structures the situation model data and directs attention, which can be detrimental when the selection and interpretation of information from the mental model results in a faulty SM (Endsley, 2000b).

It is interesting to note that although it appears that situation models can be of use in DDM, research suggests that people are not particularly effective at creating accurate situation models.

This might be due to the limited research available to conduct this review. Future research should be undertaken to understand the ability of situation models to support DDM, as well as the ability of dynamic decision makers' ability to form situation models. In particular, research should look at how observers perceive information, what are the criteria to determine important information from non-important information, how is information perceived and sorted in dynamic environments, how well is information integrated in dynamic environments, and the effectiveness of system predictions in dynamic environments.

5.1.4 System Dynamics

Within system dynamics theory, much time and effort has been focused on mental models. Unfortunately, inconsistencies among the definition of mental models in system dynamics makes it difficult to clearly understand the role of mental models in dynamic decision making. Researchers seem to agree that from a system dynamics approach, mental models mediate dynamic decision making (Cronin & Gonzalez, 2007; Elg, 1996; Sterman & Diehl, 1993). Further, an underlying assumption is that improvements in one's mental models automatically results in improved DDM. However, there does not appear to be supporting research clarifying how this actually takes place. In fact, some research has even demonstrated a lack of a direct relationship between mental models and their use in dynamic decision making. Dhawan (2006) showed that participants' mental models improved after they had training on systems dynamics, though there was no change to their dynamic decision-making abilities. These results do not support the assumption that mental models are completely intertwined with DDM.

The means/ends model proposed by Richardson et al. (1994) appears to provide the most support for the use of mental models in dynamic decision making within system dynamics, and is also applied similarly to Bryant's CECA model, though this model does not intentionally take a system dynamics approach. As is the case with all system dynamics theory, this model requires one to have a fairly good comprehension about the system and its influences in order to construct a useful model that can be used in a "planned action setting". As described earlier, dynamic decision making tasks are highly uncertain, and are often very ill-structured problems. These DDM task characteristics are not sufficiently supported by system dynamics theory, which seems to require more knowledge about the system than is often allowed within the characteristics of a DDM task. Uncertainties within the task may be too great to allow for a comprehensive structure of the system to be created. Problems that are poorly structured, such as those in DDM, may not be comparable to the systematic problems presented in much of the system dynamics research. Microworlds have very systemic, though complex, problems that allow understanding of the system, predictions, actions, feedback, repetition and learning. However, dynamic decisions are often not as well defined in real life situations as they are in microworlds.

System dynamics does however support other DDM task characteristics well. For instance, time is a key factor in a DDM task and also an important part of a dynamic system, especially those explored in research using microworld platforms.

The system dynamics perspective also assumes that the system will progress at a rate that can be managed through improvements to a mental model and that this model can then be used in dynamic decision making. The DDM environment is very complex, can have a high rate of change, have intricate interdependent relationships, and have varying levels of quality of information. These characteristics of DDM environments often do not allow time to gain a well organized understanding of the system, its influences, or second chances to correct or ameliorate decision actions.

The focus of systems thinking and system dynamics is to study the relationships between components in the systems, especially feedback loops and the patterns of behaviour generated by them (Dhawan, O'Connor, & Borman, 2006). This focus tends to be on a single system, that though complex, remains constant through time. This means that operators are asked to create a mental model of the system and then walk through the "states" of that system along a temporal dimension. This is distinct from DDM, where the system may in fact be changing, requiring the decision maker to not only look at next states, but also at alternative representations or alternative mental models (Holland et al., 1986).

Systems dynamics does adequately support decision making within stock-and-flow systems. The extent to which system dynamics supports dynamic decision making outside of microworld and system dynamic contexts is questionable. Research looking at dynamic decision making within systems dynamics should focus on how DDM task and environmental characteristics can be supported by mental models, and on the DDM contexts in which system dynamics research transferable.

5.2 Comparing requirements of DDM and Mental Models

As Chapter 3 showed in detail, dynamic decision-making involves (1) decision maker(s) (2) in a complex environment (3) attempting to accomplish one or more tasks. A key goal of this report is to explore how well the use of mental models would be likely to support the dynamic decision-making process. The sections that follow consider DDM from these three perspectives and explores the extent to which mental models might assist each DDM element. Each section will be begin by reminding the reader of the DDM requirements discussed in Section 3, followed by a discussion about how well (or not) these requirements are supported by mental models according to the literature and perspectives reviewed. We will first focus on the decision maker.

5.2.1 Decision Maker

Requirements of DDM – Dynamic decision-making environments put a number of demands on decision-makers. As noted in earlier sections, decision makers must sustain a workable compromise between the demands of the task and the need to conserve one's cognitive resources (Brehmer, 2000). To do this, they must handle the "core" decision task, and must also control the overall decision situation. Unfortunately, the DDM literature provides relatively little focus on exactly how decision-makers accomplish this task, but does assert that this is a critical requirement of being a good decision maker.

Can Mental Models Support this Requirement? – Given these requirements of the dynamic decision-maker, then, the key issue is the extent to which mental models are likely to aid them while they attempt to make dynamic decisions.

The mental models literature contains somewhat more discussion about the inner workings of decision makers, but description of the exact processes they use still remain somewhat vague. However, this literature also suggests a number of inherent limitations of decision-makers in being able to form and apply mental models. These limitations suggest key areas in which mental models may not adequately support dynamic decision makers.

<u>Cognitive limitations</u>. One of the inherent problems in applying mental models within the DDM context relates to the cognitive limitations of the decision maker. As noted, DDM requires making a series of interdependent decisions in a changing environment. Thus, it is critical that the decision

maker is able to perceive and interpret possibly a large amount of information at a relatively fast pace. This includes taking time into account, requiring the decision makers to track temporal patterns, delays and the rate of change of the scenario, all of which are part of the 'temporal awareness' of the decision maker. However, research suggests that people can only handle a limited amount of information in terms of volume and in terms of number of variables (e.g., Forrester, 1994; as cited in Doyle & Ford, 1998). This is particularly problematic for DDM, as DDM tasks take place in complex environments in which the decision maker is required to observe and interpret many changing characteristics. The inability to relate only a limited number of variables suggests that a decision maker may not be able to generate a mental model that is adequately developed to include all the details of a DDM environment.

Further complicating the decision maker's ability to form adequate mental models is the size of the model that would need to be created. In order to conduct dynamic decision tasks that are constantly changing, for example, decision makers would need to update their mental model every time they received new information in order to keep the model current. This would only be possible if new information came in at a pace that allowed the decision maker to incorporate the new information effectively into the current mental model. This could result in the decision maker developing a larger than manageable mental model and/or having to devote an undue amount of attention to maintaining an accurate model.

Another limitation noted in the mental model literature is that it is unclear whether decision makers are aware about whether their mental models are complete or not. Unfortunately, this issue is not discussed prominently. However, given a range of research and theory related to decision-making, there is some evidence that decision makers are often more confident in their decisions than they should be (Tversky & Kahneman, 1974). They may also show the same overconfidence bias in their mental models. Again, this is likely to be problematic in the dynamic decision-making environment, in which the costs of inaccurate estimations could be serious.

<u>Mental effort</u>. Although building and maintaining mental models are core activities in the control of dynamic complex systems, dynamic decision makers are required to conduct a host of operations (e.g., plan actions, control movements), all of which use cognitive resources. This suggests that mental models are more likely to be helpful when decision makers are motivated to create and use these models.

Subsequently, decision makers are often required and/or motivated to save resources where they can. This may mean that mental models are built based on partial pieces of evidence (Besnard, Greathead, & Baxer, 2004). As a consequence, decision makers may settle on a solution that they deem to be good enough even though it may be suboptimal. This is problematic as the consequences of flawed mental models can be disastrous when operating within complex dynamic system.

There are other ways noted in the literature in which dynamic decision makers try to reduce their mental efforts as well. For example, operators in critical systems sometimes would rather lose some situation awareness rather than spend time gathering data, which could mean a loss of control of the dynamic situation (Besnard, Greathead, & Baxter, 2004). Therefore, operators save resources when possible by using mechanisms such as selective memory and heuristics. This also means that they build mental models that contain partial rather than complete information. That is, they satisfice rather than optimize and settle on a solution that they deem to be "good enough". (Besnard, Greathead, & Baxter, 2004). Markham and Gentner (2001) also argue that people shift to using learned rules rather than mental models for reasoning as they gain experience with a domain. With such experience, people are able to access their stored knowledge of the outcome rather than

carry out full mental simulations of the behaviour. This may mean that when they have experience within a given domain, decision makers may tend to use heuristics rather than mental models to make dynamic decisions.

Heuristics and biases. Optimal dynamic decisions require a consistently critical stance to the emergence of new approaches and creative solutions. For example, seeking disconfirming evidence can indicate ways in which one's conceptual model is not an accurate representation of the situation. In many situations, this kind of information is more valuable than confirmatory evidence (Bryant, 2004). However, one of the problems with mental models is that they are not necessarily conducive to giving adequate weight to new information. Sustaining accurate mental models can be cyclical. Specifically, the current mental model can assist the collection of information, and that information is then used to alter the mental model. However, as argued by Besnard, Greathead, and Baxter (2004), we seek out information that supports our current belief of the situation. If the dynamic decision maker already has a flawed mental model of the situation, the new information selected and integrated by the decision maker will be the information that supports current beliefs (often in contrast to more accurately calibrated beliefs). Subsequently, this new information will just make the mental model more erroneous. With the pace of many dynamic decision-making environments being relatively fast, it seems likely that the "pull" to stick with safe and established models will often be stronger than taking the time to revise those models to include new (and potentially more accurate) information.

5.2.2 DDM Environments

***Requirements of DDM* –** The environments within which DDM occurs have a number of distinct features. They are characterized by high levels of complexity, and the sheer number of diverse goals often in play. There are also often many different forms of feedback that are relevant, and delays within the feedback systems can impose additional demands on decision makers.

Can Mental Models Support this Requirement? – The key issue, however, is whether (and if so, how) the mental model construct might help manage these issues.

Complexity. Brehmer and Allard (1991) define the complexity of the situation as relative to the capacity for the decision maker to control the number of processes, goals, action alternative, and side effects of the system. This suggests that the bigger the scope of the decision-making environment, the more information the decision maker would be required to perceive and integrate. For example, a military forces commander may be required to identify the mission goals, identify the resources available to achieve the goals, anticipate the enemy's actions, anticipate consequences of given orders given, etc. As already noted, decision makers have a limited cognitive capacity with respect to perceiving and integrating information. Therefore, the more complex the DDM environment, the less likely that the decision maker will be able to develop a detailed and accurate model.

Besnard, Greathead and Baxter (2004) argue that mental models of DDM tasks are likely only correct at early stages of the interaction. They state that interactions evolve with time and the situation may degrade (e.g., due to an emergency). The mental model then gets simplified and becomes based on correlations between system elements rather than new information.

Accepting the notion of pervasive limitations in human cognitive capacity, the broader or bigger the scope that the decision maker must consider logically implies less depth or detail that can be included. This 'breadth' versus 'depth' relationship is not new to studies of cognition, but the

effects, tradeoffs and optimizations and how individuals can find the best balance do not appear to have been explored in detail in either the mental model or DDM literature.

An additional nuance of complexity likely to impact on the ability to use mental models for DDM relates to the natural levels of coherence and order within a given situation. There is a clear sense in the mental model literature that one of the important functions of these models is that they promote coherence, the ability to understand even diverse linkages among elements. Mental models do not necessarily have to be wholly consistent, one might argue, but they have to make sense of how diverse elements might fit together. In a sense, mental models can help to represent a complex "story" in a way that makes sense. The potential problem within DDM environments, on the other hand, is that these environments are not necessarily conducive to creating coherence from disorder, and for understanding the causal structure among diverse elements. This suggests that mental models may be more difficult to form in DDM environments.

Feedback. Denzau and Roy (2005) state that the best conditions under which to form mental models are those in which there is frequent feedback about the situation. This suggests that when dynamic decision-makers encounter situations that provide timely and accurate feedback, they will be able to develop the appropriate mental model. This could assist their subsequent interactions with the "system" and make them more effective, because mental models help to simplify the environment. However, decision makers are not always able to learn the true models in situations in which feedback is infrequent or non-existent (Denzau & Roy, 2005). However, the DDM literature lists feedback delays as a characteristic of DDM environments. Such delays in feedback are problematic for forming mental models (indeed for learning in general) because people have trouble dealing with long time delays between actions and feedback (Fu & Gonzalez, 2006; Sterman & Diehl, 1993). Subsequently, decision makers will have difficulties incorporating the delayed information into their mental models. The impact of this is that decision makers will not be able to form true mental models of a dynamic situation (Denzau & Roy, 2005).

According to Bryant (2004), it is not the amount of data that is the paramount when forming mental models, but rather the quality and value of the information to the issue at hand. However, the quality of the feedback information in dynamic decision environments is described as variable (Brehmer & Allard, 1991). Therefore, when dynamic decision makers receive high quality feedback, such information will support their mental models. On the other hand, when dynamic decision makers receive poor quality feedback, such information will lessen the validity of their mental models.

The ordering of the feedback also has an impact on the ability to create mental models. Zwaan (1999) states that people prefer to incorporate information in chronological order. Therefore, information that is presented outside of chronological order is hard to comprehend and integrate into an accurate mental model. In complex DDM environments, feedback is provided to decision makers when and where available. With no guarantee that feedback will be provided with chronological accuracy, decision makers might have difficulty incorporating new information. This feature of DDM environments may promote inaccurate or incomplete mental models.

5.2.3 DDM Tasks

Requirements of DDM – The DDM literature outlines several key characteristics of DDM tasks. As noted earlier, such tasks are often characterized by being highly interdependent, involving high levels of uncertainty and having time as an important element. Such tasks are often ill-structured, in the sense that it may be difficult for decision makers to fully identify all the relevant features of a

given problem. These features of DDM tasks are likely to impact on the usefulness of mental models from several perspectives.

Can Mental Models Support this Requirement? – As a whole, the nature of typical DDM tasks is likely to pose challenges for the use of mental models.

One reason for such challenges is due to time. As noted earlier, time is a key factor in many DDM tasks. That is, DDM decisions need to be made in real time, which means that decision makers do not always have control over when and where to make the decisions (Brehmer & Allard, 1991). A potential problem with creating mental models, however, is that they take time and energy to form, and it cannot be assumed that a person entering a new situation will be able to spontaneously form a new and unfamiliar mental model. The literature seems to argue that this might be possible if they enter a somewhat familiar situation or one with which they have had previous experience. However, if time is a factor (as it is in DDM environments) forming a usable mental model may be precluded.

Where mental models are likely to help in very time limited situations is where they already exist and can be brought to bear on the situation at hand. This is evident in the literature comparing the performance of experts and novices. Experts are often assumed to be faster because they have functional mental models that help them to perform tasks in a more timely fashion. However, according to Endsley (2000b), time is also a key factor in the formation of a situation model. When using a situation model, it is critical to know how much time is left until some event occurs or until an action must be taken. Knowing the rate at which the situation is changing allows for the projection of future situations. Similarly, the literature also suggests that additional aspects of time must also be included in the mental model. This includes knowing the present time, how long it takes for actions to show their effects (feedback), recognizing changes in the world, and recognizing when an updated mental model is required.

The dynamic decision environment is also inherently uncertain: the environment changes autonomously and as a result of the decision maker's actions and the system has aspects that are not visible to the decision maker (Brehmer, 1992). This feature of DDM tasks is likely to have negative implications for the decision maker's ability to form mental models. As stated by Denzau and Roy (2005), the best conditions in which to form mental models are relatively simple situations in which all or most of the information is known. The description of the ideal context for the formation of mental models most prominent in the available literature is that of a clearly bounded problem space, in which the entire problem is transparent, known, and amenable to seeing clear linkages among the component parts of the problem space. DDM tasks, on the other hand, are often highly ambiguous, containing multiple interdependent parts and having high levels of uncertainty around each part. This, of course, does not mean that mental models cannot be helpful, simply that the limitations of whatever models can be formed should be recognized.

5.3 Conclusion

The goal of this review was to attempt to understand the nature of mental models in dynamic decision-making and the role that they play in this complex process. Although there are certainly many different ways in which mental models are likely relevant to DDM, the literature in this area is unfortunately at a relatively early stage of development, and is not currently mature enough to provide a full answer. This is true from both the perspective of mental models in general and in relation to dynamic decision-making.

In terms of mental models, although there is good agreement about the potential importance of mental models, there is little consistency in the instantiation of this concept, so much so that the existence of mental models is assumed as the starting point with little true description of what the views of mental models actually are. Ironically, one of the dangers of the mental model concept is that it seems to have had such intuitive appeal that researchers and theorists seem to assume that everyone else shares the same definition of the construct that they have. More so, effectively capturing mental models still remains elusive. There is agreement that attempts to measure mental models may in the process change them, and that what information is captured may or may not be related to a decision maker's mental model at all.

Within the realm of dynamic decision-making, it seems reasonable to look for ways in which decision makers might be able to simplify their environment, and to posit that perhaps mental models might be one way in which they might do this. If, as some have argued, people are able to form models of the workings of complex physical systems, they might also be able to use similar processes to understand and to make sense of dynamic environments. Certainly, there are some key linkages that show the potential role of mental models in DDM. On the whole, however, there are also many ways in which the current approaches to understanding mental models may be too underspecified to be able to manage the complexities of decision-making in the DDM environments. Perhaps not surprisingly, we would argue that the more constrained situation model approach is the most viable current candidate for being able to serve the requirements of the DDM environment. Hopefully, further development of this area will assist the development of clear linkages among the mental model and DDM domains.

An underlying assumption throughout the dynamic decision-making approaches is that there is a link between mental models and the quality of decision making; however, research suggesting improvements to mental models results in improved decision making was not found. While a lack of support does not mean that the assumption is incorrect, it does question the assertion. Further exploration on the link between improvements in both aspects should be empirically explored (though it is acknowledged that determining the nature of the relationship is confounded by the aforementioned issues with measuring mental models).

A number of inherent limitations in decision makers forming mental models (i.e. limited working memory, biases, erroneous mental models, etc) suggest key areas in which mental models may not adequately support dynamic decision-makers. Compounding these limitations are complex DDM environments with delayed (at best) feedback. Since the literature is consistent in finding that mental models are often erroneous under the most ideal circumstances, it is reasonable to assert that the DDM conditions would only add to those errors.

Nonetheless, further exploration of the nature of both mental models and their potential intersection with DDM will hopefully be possible as research and theory progress, and as the literature matures. The section that follows explores a range of possible future questions and issues that will further this goal.

6. Future Research Recommendations based on Gaps in the Literature

This section includes two tables that summarize gaps in the literature that have been touched on in the previous sections of the report. The first table will look at what mental models research would have to explore to better serve DDM and the second table looks at mental models research questions in general.

Table 4: Mental Models and DDM

Research Issue	Research Questions
Limits to mental models	How are mental models formed when the system variables are interdependent? How do mental models incorporate interdependent variables? Can mental models incorporate information when the system is changing quickly? Is there a limit to the rate of change? Do decision makers use more than one mental model in such cases? Can mental models be formed when the decision maker is lacking clear goals? Can mental models be developed in complex environments? How useful would such models be? To what extent do mental models improve dynamic decision making? In dynamic decision making tasks, what constitutes effective mental models? Once familiar with a system, do experts replace mental models with other cognitive structures? How do inconsistent models impact on DDM effectiveness? How do dynamic decision makers choose between inconsistent mental models when making dynamic decisions? What are the criteria for choosing between inconsistent models? When do people realize they have inconsistent mental models? How is it that people register that they have inconsistent mental models? How is information perceived and sorted into mental models in dynamic environments? Can people have multiple mental models of the same system, at different abstraction levels? How different are models of the environment and models of physical systems, especially since the latter should form part of the former?
Awareness of mental models	Are dynamic decision makers aware of their mental models of the system? Can they be made more aware? What skills do dynamic decision makers need to ensure they form accurate mental models? Are there ways for decision makers to become aware of their mental models inaccuracies? To what extent is the decision maker ‘a part of’ the mental model? How do

	decision makers to know when the 'best time' is to make a decision? Or are decisions made only when they must be? Are dynamic decision makers aware of their perception biases and how they impact on their mental models? Are there questions decision makers can ask themselves to reduce the effects of these errors? To what extent do decision makers consciously run their mental models?
Feedback	Can dynamic decision makers be trained to better incorporate feedback delays into their mental models? Do mental models incorporate feed forward loops? If so, how useful are they in making dynamic decisions? How does feed forward information impact mental models? Can mental models be altered to better incorporate feedback or feed forward information?
Individual differences	Are there individual differences that make some dynamic decision makers better at formulating mental models? Can these attributes be taught to other dynamic decision makers?

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Table 5. Mental Models

Research Issue	Research Questions
Mental models in general	What are the links between the different types of mental models? Are there actually different types, or are they all part of the same cognitive construct? Are there aspects of creating and updating mental models that are readily learned? How quickly are mental models developed? How are mental models different from any knowledge stored in the brain? Are mental models transitory or more permanent? Is there a point where mental models become too unwieldy? What Is the role of deductive versus inductive reasoning in mental models errors?
Measuring mental models	What are the most effective methods for measuring mental models? Is the effectiveness of the measurement method dependent on the situation? Can measurement methods be combined together effectively, resulting in a more coherent understanding?

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(U) The complex and dynamic nature of various types of operations pose specific cognitive challenges on the decision−making process that the current training regiment of military commanders does not directly address. Therefore, DRDC Toronto is interested in researching training techniques to prepare Canadian Forces (CF) commanders and staff for decision−making in such complex and dynamic environments (12sk). This report provides a review of relevant DDM literature and mental models literature as it relates to DDM.

DDM consists of (1) decision maker(s) (2) in a complex environment (3) attempting to accomplish one or more tasks. DDM is required in environments with high risk and complexity, and involves the performance of tasks requiring multiple steps, that are inherently time sensitive, interdependent, and which exert influence over the surrounding environment as well as being influenced by it. Dynamic decision−making has been explored from different perspectives, including systems theory, psychology, and control theory from the engineering domain. These perspectives put varying amounts of focus on different aspects of DDM. What is common to all of these approaches are the assumptions that whether forming models of complex systems or making intuitive decisions based on very little information, people tend to form some sort of mental model to undertake DDM. At a broad level, mental models can be described as personal mental representations of our world. Although there is no one agreed definition of mental models, they are generally recognized to serve three key functions: to describe, to predict, and to explain our world. The aim of this report was to explore how mental models are understood across the propositional logic, physical systems, situation model, and system dynamics perspectives. Few similarities in the descriptions of mental models were found between the domains reviewed in this report. In addition, mental models were found to be subject to a range of shortcomings that impact the accuracy of mental models (e.g., limited cognitive capacity, erroneous causal links, based on incomplete information, systemic errors).

The extent to which DDM could be supported by each of the unique approaches to understanding mental models was assessed, as well as an exploration of how well the use of mental models would be likely to support the dynamic decision−making process. This review closes with an outline of the mental models research that needs to be better explored to serve DDM, as well as an outline of the general mental models research questions that should be addressed in future research.

(U) Le caractère complexe et dynamique de certains types d’opérations pose des problèmes cognitifs particuliers au processus de prise de décisions que l’instruction actuelle des commandants militaires ne traite pas directement. RDDC Toronto est donc à la recherche de techniques d’instruction qui permettront de former les commandants et les membres d’état major des Forces canadiennes (FC) à la prise de décisions dans des environnements complexes et dynamiques (12sk). Le présent compte rendu renferme un aperçu de la documentation sur la PDD et sur les modèles mentaux associés à la PDD.

La PDD implique la participation (1) d’un décideur, (2) dans un environnement complexe, (3) qui tente d’exécuter une ou plusieurs tâches. La PDD est nécessaire dans des environnements complexes où le risque est élevé. Elle implique l’exécution de tâches requérant des étapes multiples, pour lesquelles le temps est important, qui sont interdépendantes et qui exercent une influence sur le milieu environnant, tout en étant influencées par lui. La prise de décisions dynamique a été explorée à partir de différents points de vue, notamment la théorie des systèmes, la psychologie et la t héorie de

contrôle dans le domaine de l'ingénierie. Ces points de vue mettent l'accent, à divers degrés, sur différents aspects de la PDD. Une hypothèse est commune à toutes ces approches : qu'il s'agisse de former des modèles de systèmes complexes ou de prendre des décisions intuitives à partir de très peu de renseignements, les gens ont tendance à développer une certaine forme de modèle mental pour effectuer une PDD.

De façon générale, on peut décrire les modèles mentaux comme des représentations mentales de notre monde. Bien qu'il n'y ait aucun consensus sur la définition des modèles mentaux, ces derniers sont généralement reconnus pour être associés à trois fonctions clés : décrire, prédire et expliquer le monde qui nous entoure. Le présent compte rendu a pour but d'explorer comment les modèles mentaux sont compris du point de vue de la logique des propositions, des systèmes causals, du modèle de situation et de la dynamique des systèmes. On a trouvé peu de similitudes dans les descriptions des modèles mentaux entre les domaines examinés dans la présente analyse. En outre, on a découvert que des modèles mentaux étaient sujets à une variété de lacunes influençant leur exactitude (p. ex., capacité cognitive limitée, liens causals erronés fondés sur des renseignements incomplets, erreurs systémiques).

On a évalué jusqu'à quel point la PDD pouvait être appuyée par chacune des approches uniques à la compréhension des modèles mentaux, de même qu'on a exploré jusqu'à quel point l'utilisation de modèles mentaux appuie le processus de prise de décisions dynamique. L'examen se termine sur les aspects de la recherche sur les modèles mentaux devant être mieux explorés pour servir la PDD, de même que sur un aperçu des questions générales relatives à la recherche sur les modèles mentaux qui devraient être traitées.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

(U) mental models; dynamic decision making; microworlds; system dynamics; cognition; control theory; situation models